Analysis of initial effluent degradation : a study at two Montana water treatment plants

by Karen Elizabeth Bucklin

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Environmental Engineering
Montana State University

Abstract:
The initial effluent from a granular media filter after a backwash is of higher turbidity than the effluent later in the filter run. Various theories have been put forward to explain this phenomenon, known as' "filter ripening", and to determine the source of these higher turbidity readings. Several studies have shown that during this period of higher, turbidity an increase occurs in the numbers of microorganisms, including Giardia, which pass through the filter. The research conducted here attempts to answer these questions and is unique because the post backwash "filter ripening" stage has been examined in two operating municipal water treatment plants, whereas previous studies have mainly been conducted within pilot plant scale studies.

Turbidity samples were collected during the post backwash period, both as grab samples and by continuously recorded monitoring. Microbiological samples were gathered at the same sample points, and were analyzed for total coliforms, injured coliforms, and heterotrophic plate count. Raw water characteristics, water treatment and chemical additions, and total plant effluent characteristics were monitored.

Incidences of higher ' than normal turbidity were evidenced at both plants, as has been shown to occur in pilot studies, during the post backwash filter ripening phase. These periods of high turbidity readings were found to show a two peak characteristic. Microbiological sampling showed no relationship between the higher turbidities and a corresponding increase in bacterial numbers. The chlorinated backwash water used in an operating water treatment plant seems to negate the relationship between the turbidity and bacterial numbers. This study also confirmed the higher recovery rates for chlorine injured coliforms using MT-7 agar, as compared to m-Endo agar, during the post backwash period. This effect was most pronounced during the initial portions of the filter run, and tapered off as the filter run progressed.

The data collected for this study confirms a dual peaked turbidity post backwash filter effluent characteristic in a full scale plant setting, but raises sane questions concerning the origins of these peaks. The data also provides sane guidelines for the minimization of these turbidity peaks.

These findings are applicable to the operation of existing water treatment plants, to provide guidelines for the production of a low turbidity effluent. It also raises questions concerning the practicality of filter-to-waste design for the post backwash filter period, in terms of the assumption of bacterial numbers being associated with turbidity during this period in the filter run.'

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AT TWO MONTANA WATER TREATMENT PLANTS

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ABSTRACT

The initial effluent from a granular media filter after a backwash is of higher turbidity than the effluent later in the filter run. Various theories have been put forward to explain this phenomenon, known as "filter ripening", and to determine the source of these higher turbidity readings. Several studies have shown that during this period of higher turbidity an increase occurs in the numbers of microorganisms, including Giardia, which pass through the filter. The research conducted here attempts to answer these questions and is unique because the post backwash "filter ripening" stage has been examined in two operating municipal water treatment plants, whereas previous studies have mainly been conducted within pilot plant scale studies.

Turbidity samples were collected during the post backwash period, both as grab samples and by continuously recorded monitoring. Microbiological samples were gathered at the same sample points, and were analyzed for total coliforms, injured coliforms, and heterotrophic plate count. Raw water characteristics, water treatment and chemical additions, and total plant effluent characteristics were monitored.

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The data collected for this study confirms a dual peaked turbidity post backwash filter effluent characteristic in a full scale plant setting, but raises some questions concerning the origins of these peaks. The data also provides some guidelines for the minimization of these turbidity peaks.

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CHAPTER 1

INTRODUCTION

It is well known that the initial effluent turbidities of a recently backwashed filter are higher than the turbidities later in the filter run (Amirtharajah, 1985; Chen, 1986; Yapijakis, 1982; Francois and Van Haute, 1985). The period of higher than average effluent turbidities is followed by a period during which the turbidities begin to slowly improve. This phenomenon, frequently called "filter ripening", has been often noted, but has not been extensively studied.

Concern about the intial portion of the filter run is due to the association of high turbidities with high particle counts (McCoy and Olson, 1986), and with high numbers of microorganisms (Logsdon and Rice, 1985; Logsdon, et al., 1985). Other studies, however, show a variable correlation between turbidity and bacteriological parameters (Reilly and Kippin, 1983; McCoy and Olson, 1986).

Regardless of the numbers of organisms associated with turbidity, high turbidities are undesirable due to the implications for disinfection. Turbidity is believed to: (1) serve as a carrier for nutrients that can result in biological activity and water quality degradation (Herson et al., 1984), (2) exert a significant demand upon the disinfectant used, resulting in a lower disinfectant residual in the distribution system (Ridgway and Olson, 1982), and (3) provide a matrix to "shield", or transport microorganisms into the distribution system (LeChavallier et al., 1984). Additionally, several studies have concluded that due to the large number of injured organisms present in drinking water, enumeration of coliforms has been underreported (McFeters, et al., 1982; LeChevallier and McFeters, 1985; McFeters and Camper, 1983; LeChevallier, et al., 1983; O'Connor, et al., 1984).

Several studies have tried to characterize and to determine the causes of the initial effluent degradation and the subsequent filter ripening period. Research by Amirtharajah and Wetstein (1980), has indicated that the period of effluent degradation is due to the backwash water remnants. Work done by Francois and Van Haute (1985), indicates that a large part of the poor quality effluent is a function of the influent water. The filter improvement period, or the period during which the effluent quality improves has been characterized by O'Melia and Ali (1978), and by Payatakes et al. (1981) as related to the accumulation of influent particles within the media over time.

The use of a filter-to-waste period at the beginning of a filter run was commonly used to control the quality of the filter effluent up to the 1930's. The procedure has not routinely been designed in newer plants but has gotten increasing attention due to concern over possible transmission of Giardia cysts. This practice may only be sufficient to avoid the initial effluent degradation peaks, since the filter ripening period generally takes place over an extended period of time. Another method of protecting the effluent quality is the injection of a polymer into the backwash water (Cranston, 1986; Harris, 1970; Yapijakis, 1982).

The polymers adsorb to the filter media, serving to "precondition" the filter.

There is a paucity of information from actual water treatment facilities investigating the period of filtration following a backwash. Most of the studies which deal with the post backwash period of the filter run have been conducted in pilot scale studies.

The research conducted herein provides a view of the post backwash filter effluent in full scale water treatment plants, and develops a hypothesis for this period, based upon observations and data collected as well as upon the literature available. In addition, some guidelines for the operation of water treatment facilities are presented, with the goal of minimizing the turbidities and bacteriological numbers associated with the post backwash period.

CHAPTER 2

RESEARCH OBJECTIVES

The overall objective of this research was to characterize the post backwash filter ripening phase of dual media filters in full scale water treatment plants. This is important in order to develop operational methods or design guidelines which minimize the magnitude and the duration of this period. The individual research objectives were:

1. To confirm the occurrence of high turbidity, bacteria and particles in the initial effluent from a filter and its association with the backwash water remnants.

2. To determine the magnitude of the components to initial degradation from the backwash water remnants and the improving phase.

3. To determine the severity of initial degradation in relation to current standards for drinking water (1 ntu) and future standards (0.2 ntu).

4. To determine the changes in initial degradation over a year with seasonal changes in raw water quality including temperature and treatment chemicals.

5. To compare the initial degradation from a conventional plant as contrasted with a direct filtration plant.

6. To develop design and operational guidelines that would minimize the detrimental effects of initial degradation.

CHAPTER 3

LITERATURE REVIEW

As mentioned earlier, there is a real lack of information regarding the initial stages of filtration in full scale water treatment plants. The only plant scale study which has focused on the initial degradation phase of a filter run reported in the literature is a 1982 report by Qureschi. An additional study which has been carried out in a municipal water treatment facility is a study in 1970, by Leslie Harris. However, Harris' investigation does not concentrate on the initial degradation of the filter effluent following a backwash. Rather, he investigated the minimization of the total filter effluent degradation by the use of coagulants in the backwash water remnants. There is much more information in the literature dealing with the mechanisms of filtration, including the mechanics of the improving effluent quality of a filter over time. There is a fair amount of data available from studies carried out on pilot plant filters, which chronicles the occurrence of high turbidity, high bacterial counts and high numbers of Giardia cysts in filter effluent during the period of time following a filter backwash.

In addition, there is a quite a bit of material covering the occurrence of coliforms, injured coliforms, heterotrophic organisms, and particle counts in water systems, and the correlation of this data with turbidity.

Initial Degradation of Filter Effluent

Amirtharajah and Wetstein (1980), with work done using a pilot scale filter, showed that the initial effluent quality from a filter used over several filter runs could be divided into three portions; the lag period, the rising limb culminating in two turbidity peaks, and the long receding limb (Figure 1). They proposed that the lag period was due to the clear backwash water remaining in the underdrain system up to the bottom of the filter media, that the rising limb was due to particles derived during collisions of the settling media at the end of the backwash, and that the receding limb was due to the dispersion of the media-derived particles from the filter with the influent, and the accumulation of influent particles within the media pores. The rising limb consists of two separate turbidity peaks; the first corresponding with the turbidity of the backwash water remnants remaining within the media, and the second corresponding with the backwash water remnants standing above the filter media, up to the backwash water gutter, following backwash.

The three stages of the initial effluent degradation have different characteristics in terms of particle concentrations. In general, the first turbidity peak, associated with the backwash water remnants within the filter media, has a quality which is characterized by the last stages of the backwashing operation. The second turbidity peak,

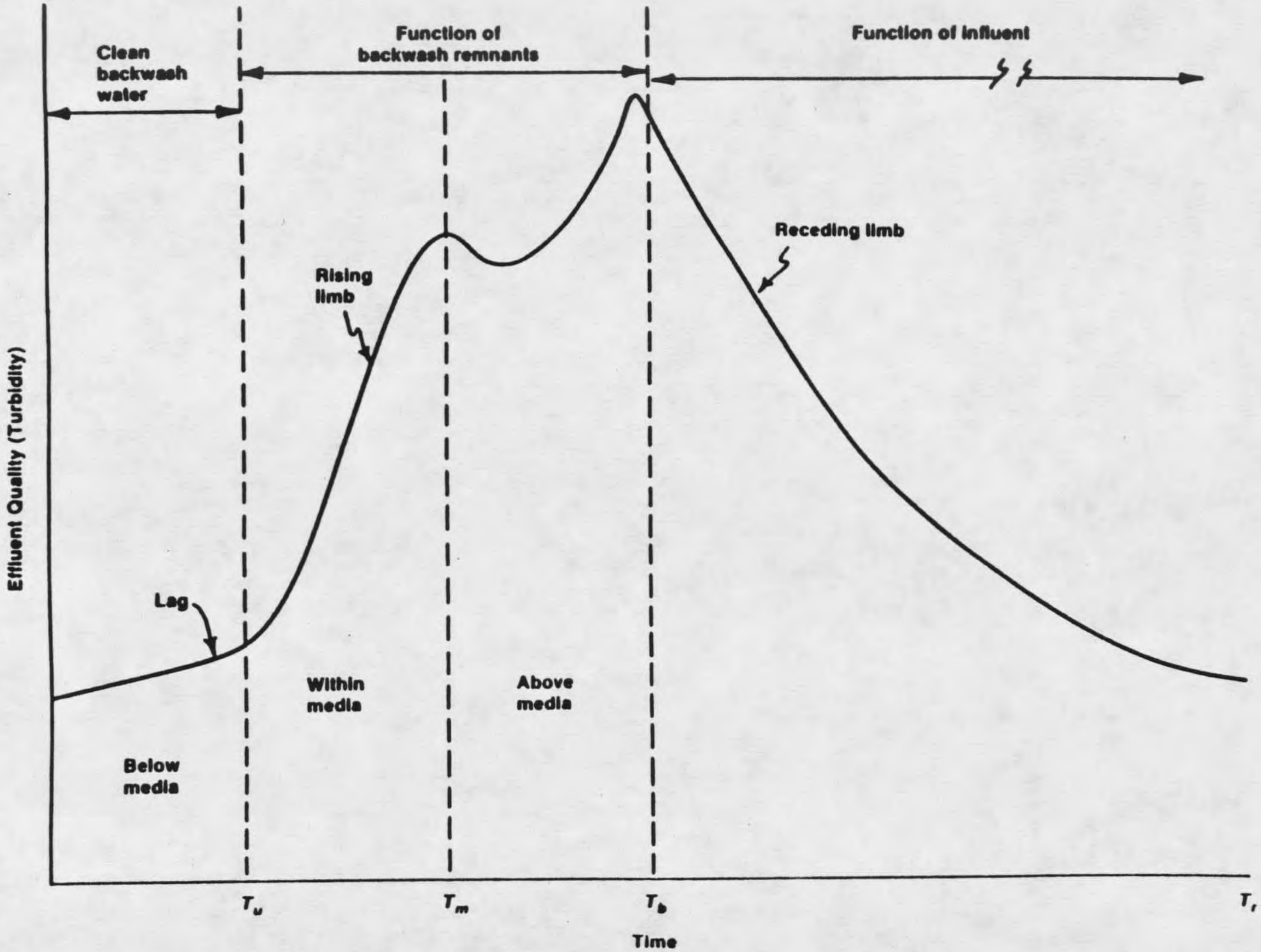

Figure 1. Characteristics of Initial Effluent Quality (Amirtharajah and Wetstein, 1980).

associated with the backwash water remnants remaining above the filter media, is the poorest quality water.

Amirtharajah (1982) has developed a model which characterizes the quality of the backwash water. The model assumes a surface renewal mechanism for particle detachment from fluidized grains to the backwash water. It is shown that the concentration of particles, C, in the backwash water are represented by;

$$C = Ke^{-(vt/d)}$$

in which ; v = backwash water velocity, t = time, d = diameter of collectors, and K = coefficient. This result indicates an exponential distribution of particles in the backwash water, and serves as a rationale for the dominance of the second turbidity peak during initial degradation.

Qureshi (1982), ran a series of plant-scale investigations at the Fridley Water Treatment Plant for the City of Minneapolis, in which filters were subjected to various backwashing rates. The study concluded that a higher initial degradation resulted when filters were backwashed at sub-fluidization rates. He also confirmed the existence of two turbidity peaks during the initial filter effluent degradation phase, and their relationship to the backwash water remnants as proposed by Amirtharajah and Wetstein (1980).

Qureshi's study was carried out, it should be noted, in a softening plant with alum addition. Turbidities from individual filters ranged from 0.5 to 1.9 ntu during the first hour of operation, while the typical turbidity during mature filter operation from one hour to 50 hours was in the range of 0.2 to 0.5 ntu. Qureshi attempted to minimize the initial degradation turbidities by addition of polymer to the backwash water.

In 1985, Francois and Van Haute described the filter ripening phase, modifying Amirtharajah and Wetstein's theory. Their experiments were carried out using a pilot scale plant utilizing domestic waste water with alum in conjunction with a non-ionic polymer. They theorize that the peak turbidity is more related to the influent water than to the backwash remnant water (95% influent vs. 5% remnant). Their research indicated that the ripening period of the filter is simultaneous with a change in the pore structure of the filter bed, and that the initial turbidity breakthrough was due to the breakdown of the initially placed weak hydroxide flocs within the pores of the media due to the rapid increase of velocity gradients as particles begin to accumulate within the media pores. The loosely deposited flocs are scoured back into suspension in fairly large amounts.

Another conclusion from Francois and Van Haute's study was that by overdosing the coagulant during the initial stages of filtration, the filter ripening peak can be reduced. They attributed this to an increased blocking rate of the media pores and dead zones.

Therefore, they summarize that the major degradation turbidity peak is assumed to be due to a lack of filter efficiency, caused by an inadequate pore structure and the passage of the initial weak flocs through the filter media. The rate of pore blocking was suggested to be strongly influenced by the chemical pre-treatment of the raw water.

Studies by Payatakes, et al. (1981), and O'Melia and Ali (1978), have shown that the improving phase of filter ripening is due to the accumulation of particles within the media flow channels. O'Melia and Ali suggested an association of the improving phase of filter ripening with the formation of particle chains, or dendrites, on the media during the initial stages of filtration. They used a pilot-scale study, with a polymer coagulant system. Payatakes, et al. (1981) showed, with simplified visual experimental data, that the main mechanism causing alteration of the geometry of flow channels within the filter could be throat clogging. This throat clogging resulted in an increase of local capture efficiency and explains the improving phase of filter ripening.

O'Melia and Ali (1978) developed an equation to model the improving phase of filtration due to the accumulation of particles and the formation of dendrites and particle chains within the media pores. The constantly accumulating particles within the media are thought to continually improve the effluent quality by the improved capture of the influent particles by the dendrites.

The equation which O'Melia and Ali developed includes both the collection efficiency of the original filter grain as well as displaying the collector efficiency of the filter grain and its associated particles collected during filtration:

$$nr = (A*n) + (N*Ap*np)*(dp/dc)^2$$

Where: nr = Single collector efficiency of a particle and its retained particles.

A = Collision efficiency factor.

n = Single collector efficiency.

N = Number of particles that act as collectors.

Ap = Collector efficiency factor of retained particles.

np = Collection efficiency of a retained particle.

dp = Diameter of suspended particles.

dc = Diameter of collector.

Cranston (1987) modified Amirtharajah and Wetstein's theory of filter ripening, calling the events the "filter ripening sequence". In the filter ripening sequence, three stages are characterized (Figure 2). The three stages are: the remnant stage, the influent mixing and particle stabilization stage, and the filter media conditioning stage. The remnant stage is associated with the backwash water remnants remaining within the underdrains, media, and above the media after backwash. Cranston noted that a peak of high turbidity may occur at this stage due to particles sheared off the media at the beginning of the filtration cycle, or at the end of the backwash, as the media particles collide with each other. The influent mixing and particle stabilization stage occurs as the influent water disperses into the coagulant-free remnant water above the filter media. This stage is characterized by the large peak in turbidity, and the cause is the partial stabilization of the previously destabilized influent particles, as they interact with the non-coagulated backwash water. The third

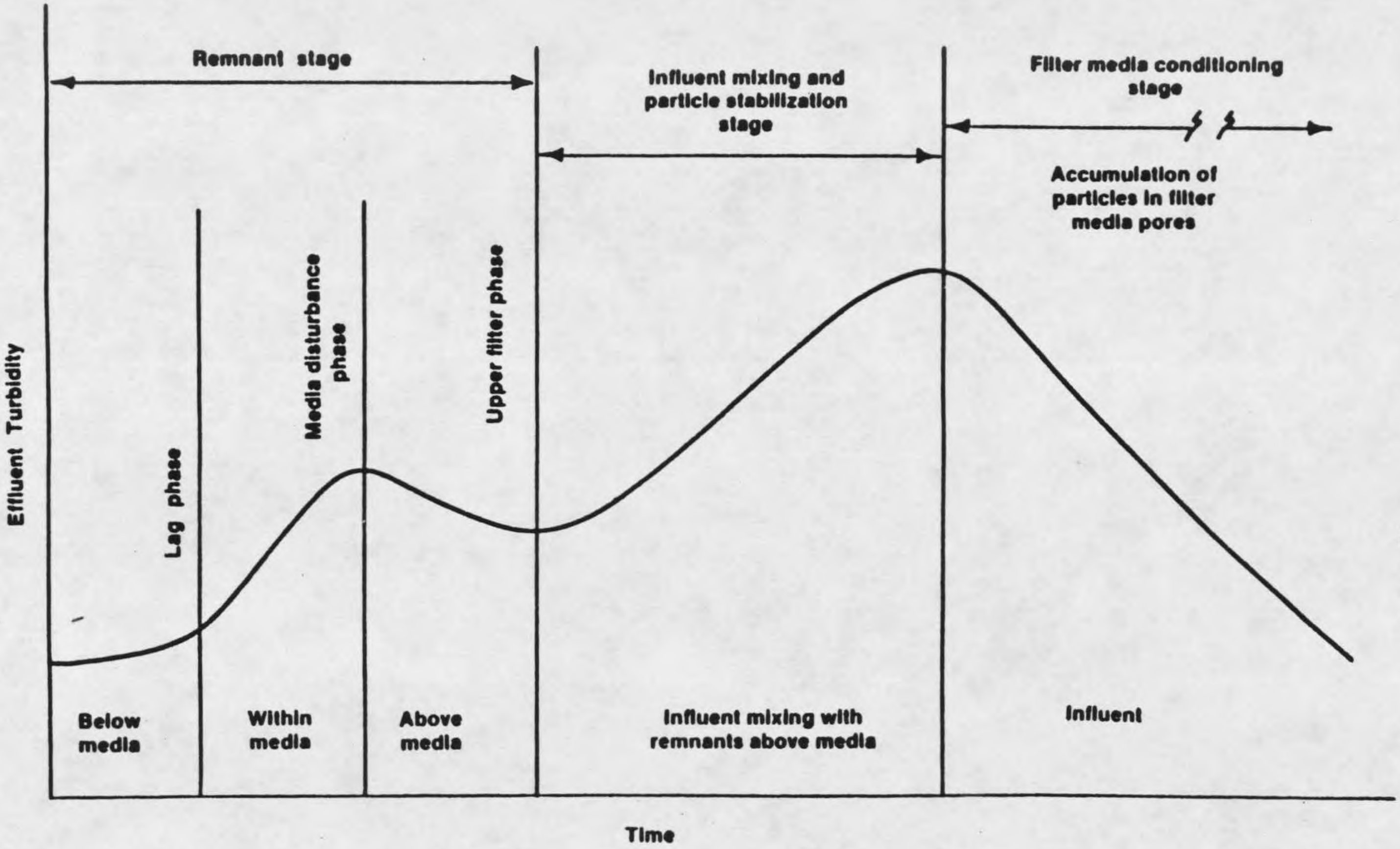

Figure 2. "Filter Ripening Sequence" (Cranston, 1987).

stage is the filter media conditioning stage, and is characterized by the accumulation of particles within the filter media, and the increased efficiency of particle removal.

Cranston also found that the use of coagulants in the backwash water as a means of reducing the magnitude and the duration of the filter ripening sequence can be very effective. He also stated that the mechanism by which this treatment becomes effective is by virtue of the fact that the coagulated backwash water remnants above the filter help to prevent the stabilization of the initial influent particles as they interact with the backwash water remnants. The coagulants or species created by the coagulants also tend to adsorb to the filter media, accelerating the particle accumulation within the media pores.

The addition of polymers to backwash water as a means of minimizing the filter ripening stage of filtration is a widely accepted idea and practice which is in use in some water treatment facilities. Several works on the subject include Harris' study at the Conta Costa County water treatment plant in California, in 1970, and Yapijakis'(1982) and Chen's (1986) experiments, using pilot plants. These studies indicate that the addition of polymer to the backwash water serves to minimize the filter ripening duration and magnitude, under both pilot and full scale studies.

Occurrence of Microorganisms in the Filter Ripening Period

One of the major problems facing the water industry today is giardiasis. Amirtharajah (1986) has recently summarized the rationale for development of mandatory filtration and disinfection regulations based on the possible transmission of Giardia cysts and viruses. Logsdon, et al. (1985) in a recent pilot scale study concluded that Giardia cyst concentrations may be higher than usual during the first portion of a filter run, and that operators should consider a filter-to-waste period at the start of a new run. Logsdon indicated that a 0.2 to 0.3 ntu rise in turbidity can be associated with rises in Giardia cyst concentrations by factors of twenty to forty. Since the ingestion of only ten Giardia cysts have been shown to cause an infection (Lin, 1985), it is quite possible that the initial degradation phase of filtration will transmit sufficient cysts to cause an infection. Some giardiasis outbreaks from filtration plants have been linked circumstantially with possible cyst transmission during the filter ripening period (Logsdon, 1985).

Logsdon and Rice (1985), in a related study, also confirmed the passage of high concentrations of Klebsiella occurred during the initial portions of a filter run, when dechlorinated backwash water was used. The Klebsiella concentrations rose sharply, as the filter run began following backwash, and then slowly declined, at about the same time as the turbidity concentrations. They went on to report that when chlorinated water was used for the backwash, no organisms were recovered for the first ten minutes of the filter run, after which the bacterial concentrations resumed as in the dechlorinated runs. Logsdon and Rice account for the low numbers of Klebsiella during the first ten minutes of the run as a result of chlorine injury to the organisms. They noted that injured and lysed organisms are a source of food for other organisms in the system, and that some injured organisms may recover to reproduce and colonize the distribution system. Logsdon and Rice concluded that the passage of bacteria during the initial filtration phase is likely to be masked by chlorination.

Al-Ani, et al.,(1984), in a pilot scale study, had similar results to Logsdon's work with Giardia and Klebsiella recovered from filter effluent. The studies of this group found that turbidity is a good indicator of bacterial and Giardia removal from filtered water, on a percentage basis. Their research, however, did not investigate the initial portions of the filter run, sampling only at 30 and 60 minutes into the filter run.

In a recent study, McCoy and Olson (1986), determined that the water quality degradation within municipal drinking water systems occurred because of intermittent short duration events that resulted in high turbidity, particle counts, and heterotrophic plate counts. They found that particle counts and turbidity were directly proportional, but that there was no predictable relationship between particle counts or turbidity and bacteriological quality. Similar results were reported earlier in 1983 by Reilly and Kippin, and in 1984, by O'Connor et al.. Reilly and Kippin concluded, from a study conducted on municipal water distribution systems, that standard plate counts (SPC) exhibited no relationship with coliform counts when the SPC was less than 50 organisms / ml.. In addition, the SPC was not dependent on low-level turbidity and varied with respect to free chlorine residuals.

O'Connor, et al. (1984), reported that there was a lack of correlation between direct cell counts and turbidity in water from distribution systems in Missouri. They also said that; "...turbidity is of no value for estimating plate or coliform counts in drinking waters."

Hudson (1981, pp7), used operating data from the Vitelma filtration plant in Bogota, Colombia, to show that bacterial counts in filtered water declined as the turbidity of the filtered water declined. This conclusion is also upheld by McCormick and King (1982), who reported that in pilot scale studies of direct filtration: "A filtered water turbidity of 0.10 ntu, which met the AWWA goal, resulted in practically complete removal of algae and coliform bacteria."

The turbidity of filtered water, whether directly proportional to microbial counts or not, is still considered a good surrogate parameter by which overall water quality can be measured. Turbidity is thought to: (1) serve as a carrier for nutrients that can result in biological activity and resultant water quality degradation (Herson, et al., 1984); (2) exert significant disinfection demand that can result in loss of disinfectant residual in the distribution system (Ridgway and Olson, 1982); and (3) provide a matrix to transport microorganisms through or introduce organisms into the system (LeChevallier, et al., 1984). Because of these effects and other pragmatic and economic considerations, turbidity measurements will continue to play a major role in drinking water regulations based on health criteria (Amirtharajah, 1986).

Incidence of Injured Organisms

As Logsdon concluded from his filter studies, discussed above, in which Klebsiella were not detected during the first ten minutes of the filter runs that were preceded by chlorinated backwash cycles, injured organisms may account for the poor recovery rates. Injured organisms present in the filter effluent may result in; (1) underestimation of the "true" bacterial count present in the water, and an overestimation of the water quality, (2) physiological recovery of the organisms, followed by regrowth in the distribution system, and a subsequent increased disinfectant demand, and (3) use of the injured organisms as "food" for the growth of other organisms present in the drinking water.

The problem of injured coliforms in drinking water has been researched by Gordon McFeters in several studies and by Mark LeChevallier, both from Montana State University. As noted by LeChevallier and McFeters (1984): "The effectiveness of the coliform group of bacteria as indicators of water quality is largely related to their efficiency of enumeration."

Not only is chlorine a source of injury, but environmental factors such as heat, freezing, sunlight, pH, and transition metals present in the water can also cause injury (LeChevallier and McFeters, 1985). Another source of repressed total coliform counts is biological interactions (LeChevallier and McFeters, 1985). The frequency of coliform detection decreases when Standard Plate Count levels exceed 500-1000 colony forming units / ml.

Several studies have shown that the enumeration of coliforms in drinking water by membrane filtration, with incubation on m-Endo medium, (the standard method most often used), often grossly underestimates the actual numbers of coliforms present. McFeters, et al., (1986), reported a 97.4% rate of injury among coliforms detected in drinking water after backwashing of a filter (Table 1). Injury rates of >90% were reported by McFeters, et al., in 1982, in coliforms recovered from the distribution system in Bozeman, MT. The average injury rate reported in this study, using m-Endo agar was 60% (Table 2).

The accurate detection of the coliform numbers present in a treated water is important in order to detect possible problems within a water treatment system. The incidence of waterborne morbidity has steadily increased over the past 20 years in the United States (McFeters, et al., 1986). The increased accuracy of enumeration of coliforms is an important tool in the prevention of waterborne disease, due to the fact that most outbreaks have been traced to deficiencies in water treatment systems and inadequate or interrupted chlorination (McFeters and Camper, 1983). Early detection of increased coliform numbers may help to "head off" waterborne disease outbreaks.

A medium developed expressly for the recovery and enumeration of coliform bacteria from drinking water is MT-7, designed to be used much the same as m-Endo, as a membrane filter medium. This medium has been proven to recover as many as three times (LeChevallier, et al., 1983) as many coliforms as m-Endo agar, the standard method (APHA, 1985), from drinking water in Bozeman, MT (Figures 3 & 4). In another study, MT-7

Table 1. Detection of Injured Coliforms in Three New England Water Treatment and Distribution Systems.*

Sample No.	Sample Source	No. of Samples	No. of Confirmed Colonies per 100 mL detected on: m-Endo LES	MT-7	% Injury	% False Negative
1	Throughout System	71	0.3	9.5	96.8	79
2	Water Leaving Treatment Plants	46	0.2	5.7	96.5	69
3	Filter Backwash	1	18	136	86.7	
4	After Backwash	1	5	42	97.4	82
5	Pipe Break	28	0.9	35.3	97.4	82
6	1 wk After Pipe Break	11	0	67.5	100	100
7	After Dis-infection of New Main	1	0	11	100	100

* Adapted from McFeters, et al. (1986).

Table 2.. Media and the Recovery of Injured and Healthy Coliforms from Water. [a*]

Medium	% Recovery (range)[b] Injured	Healthy	% Deoxycholate or Related Compounds
Group I			
Triple sugar iron	181	106	0
Nutrient alginate	125	88	0
Minerals modified glutimate	99	106	0
Tergitol 7	86 (71-101)	99	0
Boric acid	84	92	0
TLY + o.1% Tween 80	72	ND[c]	0
Group II			
Lactose broth	72 (47-98)	102	0
m-Endo	66 (30-102)	93	0.1:0.005[f]
Lauryl tryptose	56 (34-79)	98	0.01[f]
Levines EMB	42 (37-47)	119	0
3V	39	95	NA[g]
Purple serum	38	56	0
EE	38	106	2.0[d]
Brilliant green bile 2%	34 (18-51)	106	2.0[d]
Deoxycholate lactose	26	94	0.05
Group III			
Eosin methylene blue	24 (7-42)	102	NA
Violet red bile	12	99	1.5[e]
m-FC at 44.5 C	7 (4-10)	105	1.5[e]
MacConkey	5	97	0.1[e]
GN	4	71	0.05
TLY-D	2	82	0.10
XLD	0	40	0.25

a Coliforms tested include: Escherichia coli (two strains), K. pnemonia, C. freundii, and Enterobacter aerogenes.

b (Percent recovery) = ((CFU selective medium)/CFU TLY) * 100). Injury was between 90 and 99%. The range for injured coliforms is calculated from seven repetitions, using five coliforms over a 1 year period.
TLY = tryptic soy broth without dextrose, i% lactose, 0.3% yeast extract and 1.5% agar.

c ND, not done.

d Oxgall.

e Bile salts.

f Lauryl sulfate.

g NA, Not Available.

* Adapted from McFeters, et al. (1982).

recovered 8 to 38 times the number of coliforms from drinking water distribution systems in New England communities (McFeters, et al., 1986). These studies show that the possible passage of injured organisms during filter ripening has important effects not only in relation to overall finished water quality but also influences the possible regrowth of organisms in the distribution system.

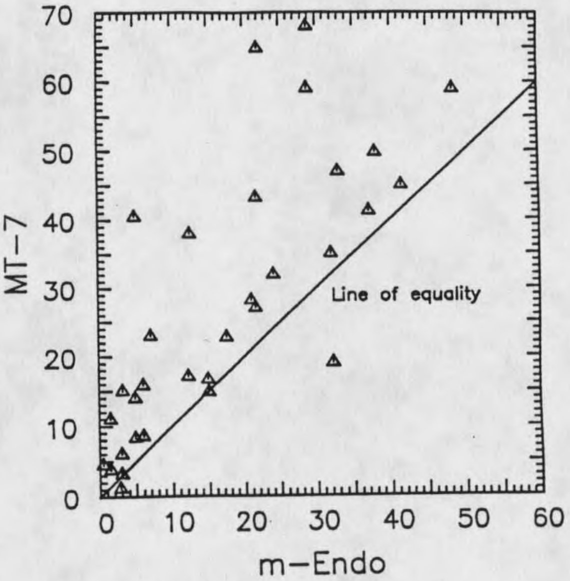

Figure 3. Comparison of Coliform Recoveries from Water Samples on m-Endo and MT-7 Agars. Counts Are Represented as Relative Values. (LeChevallier, et al., 1983).

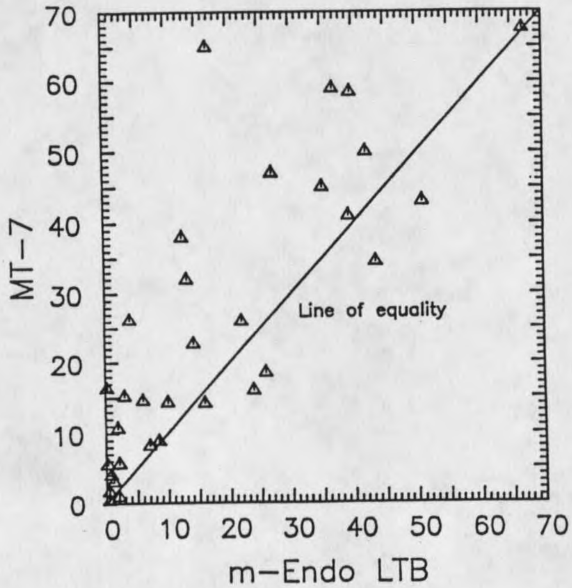

Figure 4. Comparison of Coliform Recoveries from Water Samples on m-Endo Agar with LTB Resuscitation and MT-7 Agar. Counts Are Represented as Relative Values. (LeChevallier, et al., 1983).

CHAPTER 4

EXPERIMENTAL

Site Descriptions

The experiments for this study were carried out at two municipal water treatment plants. The water treatment plants involved in this study were; the Bozeman Water Treatment Plant, located in Bozeman, MT (BWTP), and, the Missouri River Water Treatment Plant, in Helena, MT (HWTP). Each of these facilities is a 10 MGD capacity plant, and each utilizes eight dual media filters.

The Bozeman Water Treatment Plant (BWTP)

The BWTP uses a direct filtration scheme of treatment (Figure 5). The raw water is treated with bentonite and a cationic polymer (Magnifloc 587C, CatFloc T and CatFloc TL were used over the course of this study) (Table 3). The plant is a gravity flow system, with flocculation and filtration of the water (Figure 6). Prior to storage in a clear water reservoir, the filtered water is chlorinated and fluoridated. The detention time for the clear well is about two hours. Average filter flow rates vary, from about 1.7 gpm/ft^2 to 4.7 gpm/ft^2, depending upon the municipal demand. The surface area of a filter is 196 ft^2. During the peak demand months of the summer, the water supply is augmented by the use of a creek supply (Lyman Creek). The water from

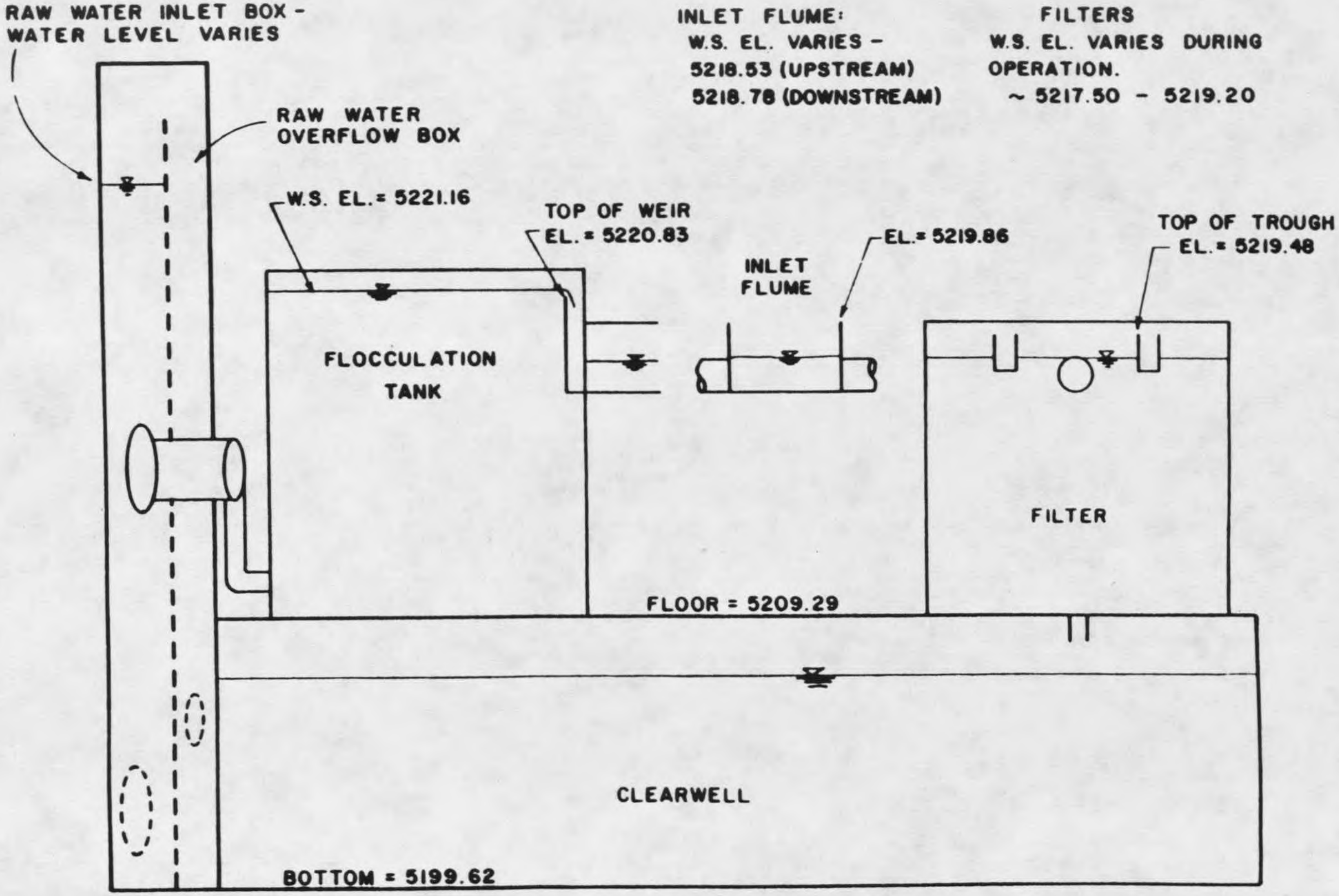

Figure 5. Layout of Bozeman Water Treatment Plant.

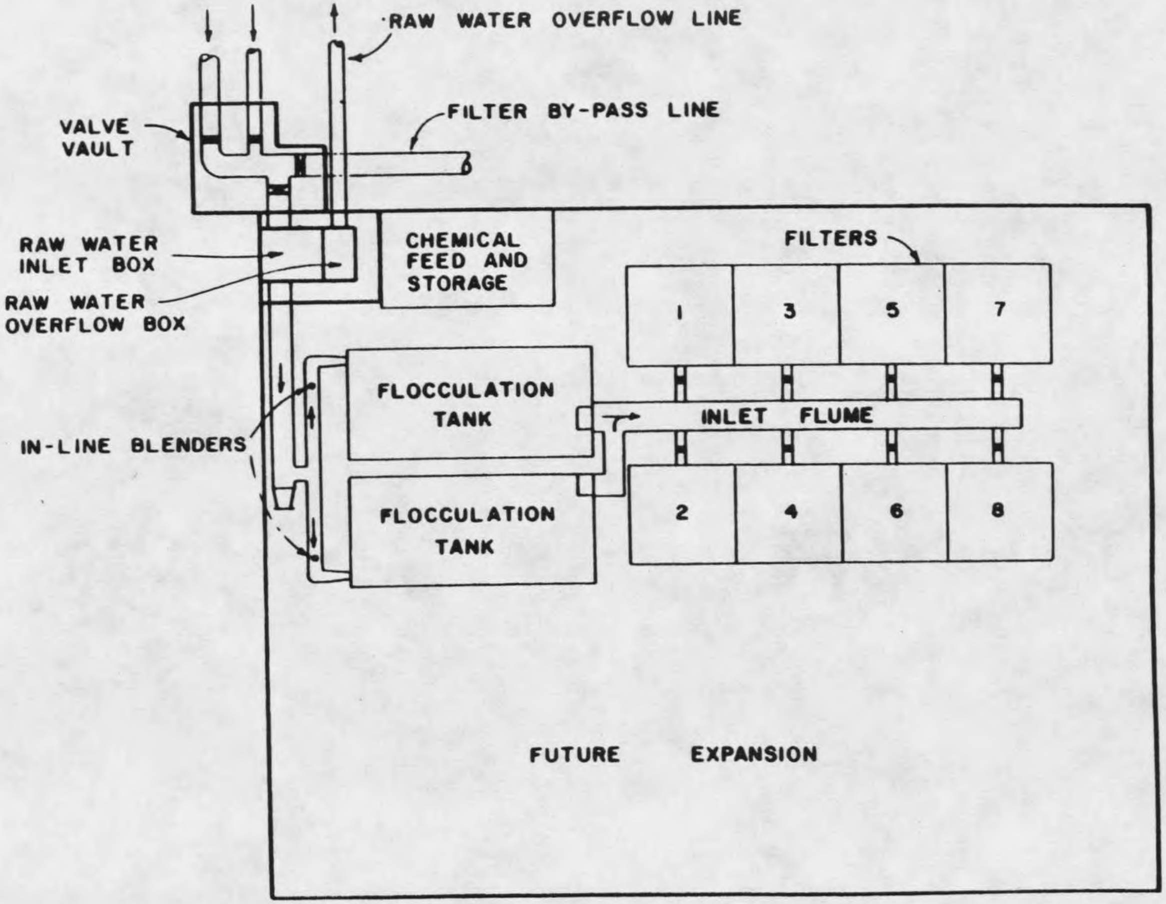

Figure 6. Layout of Bozeman Direct Filtration Water Treatment Plant.

Lyman Creek is not treated at the BWTP. Instead, the water from the creek is simply chlorinated and admitted to the distribution system (Figure 7).

Table 3. Polymers Used at the Bozeman, Montana and Helena, Montana Water Treatment Plants

DATE	Bozeman Water Treatment Plant (Cationic)	Helena Water Treatment Plant (Cationic)	Helena Water Treatment Plant (Non-ionic)
1-1-86	CatFloc T	Nalco 8105	Nalco 8170
4-1-86	Magnifloc 587C		
4-22-86	CatFloc T		
5-1-86	Magnifloc		
6-4-86	CatFloc TL		
6-6-86	CatFloc T		
6-12-86	Magnifloc		
7-21-86	CatFloc T		
2-9-87		Magnifloc	

One of the distinguishing features of the BWTP system is the excellent quality of the raw water. The raw water source for this facility is surface water from mountainous sources, including mountain streams (Hylite and Sourdough Creeks) and mountain reservoirs (Hylite Reservoir), all of which are filled by runoff from rainfall and snowmelt. Year round raw water turbidities generally remain below 1.0 ntu.

However, during the springtime, the raw water turbidities can "spike", causing episodes of higher than average turbidities, ranging from 10 to near 30 ntu. During the first year of operation (1983), turbidity spikes as high as 60 to 80 ntu occurred. The heavy logging in

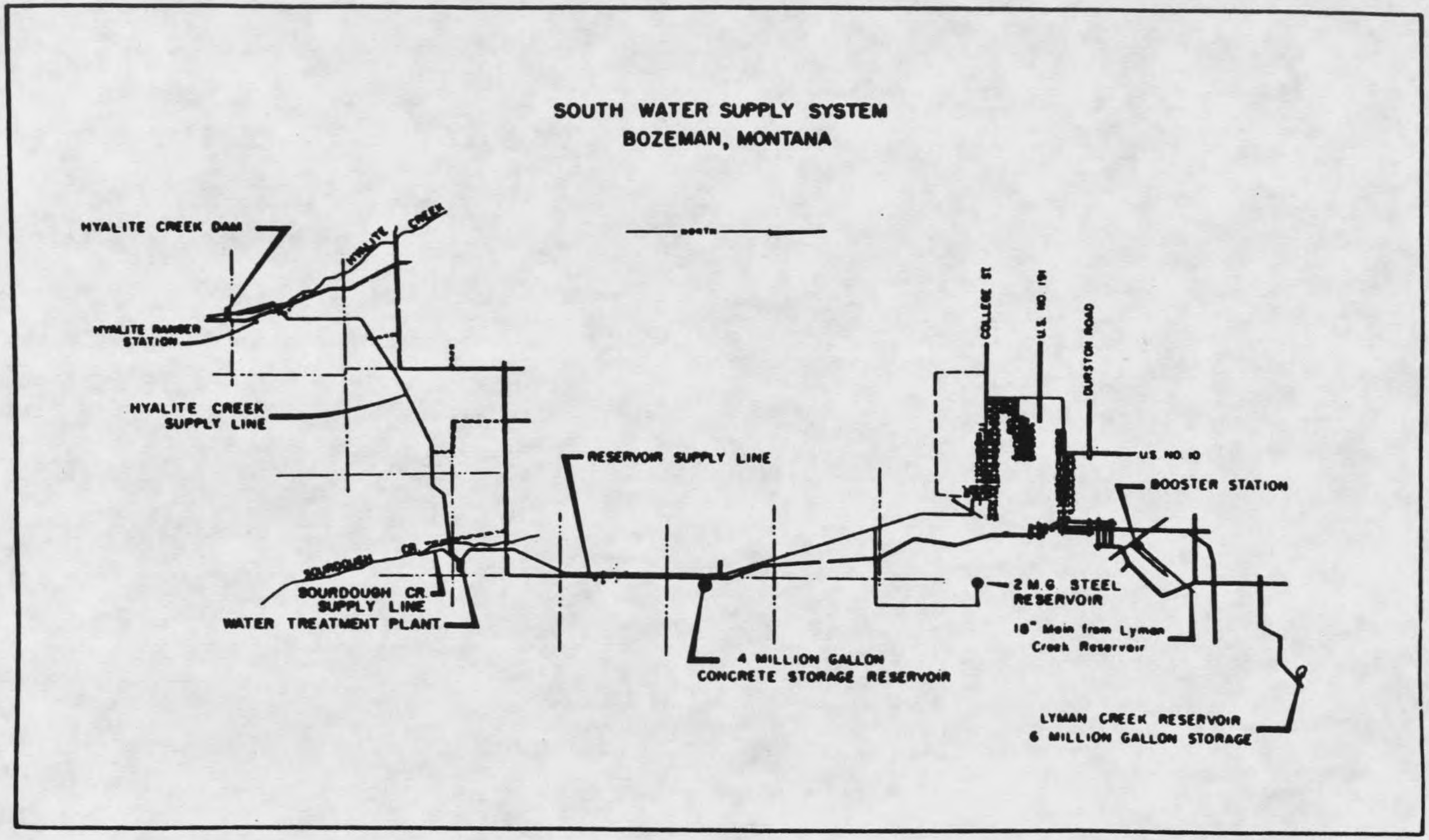

Figure 7. Raw water Sources and Distribution System.
City of Bozeman.

the water supply area probably is a contributing factor of the turbidity spikes, since they seem to occur after especially warm spring days where the snow melt is great, or immediately following rainstorms during both the spring and summer. It is during these episodes of raw water turbidity spikes that the direct filtration treatment scheme is least effective, although even during these times, the plant effluent turbidities remain less than 1.0 ntu.

Also, the plant's total effluent quality, in terms of turbidity, varies somewhat depending on the filter flowrate maintained. Again, the effluent turbidities generally remain below 1.0 ntu, although during high filter rates, the individual filter effluent turbidities are sometimes in the 1.0 to 1.2 ntu range for short periods of time.

The Missouri River Water Treatment Plant (HWTP)

The HWTP uses a conventional treatment mode of operation (Figures 8 and 9). The raw water source is the Missouri River, from which water is taken at the Canyon Ferry Dam. Raw water entering the plant is pre-chlorinated, followed by the addition of sodium hydroxide, alum, non-ionic polymer (Nalco 8170), cationic polymer (Nalco 8105), and powdered activated carbon. The water is then flocculated, allowed to settle, and filtered. The filter flow rates at the HWTP remain fairly constant, at 1.3 to 2.6 gpm/ft^2. The surface area of a filter is 270 ft^2. Following filtration, the effluent is chlorinated and fluoride is added in the clear well. Two more clear wells follow in line, prior to

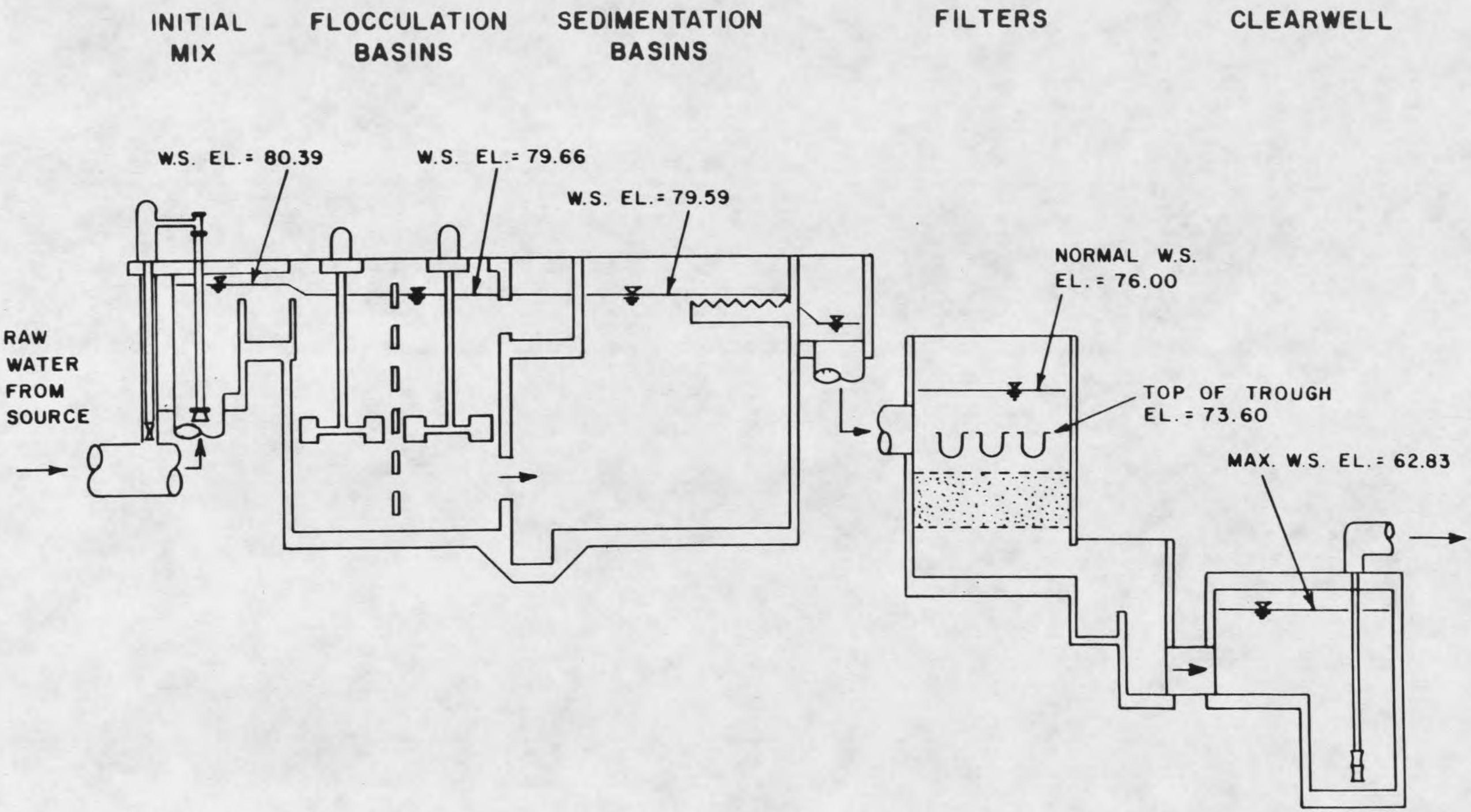

Figure 8. Layout of Missouri River Water Treatment Plant, Helena.

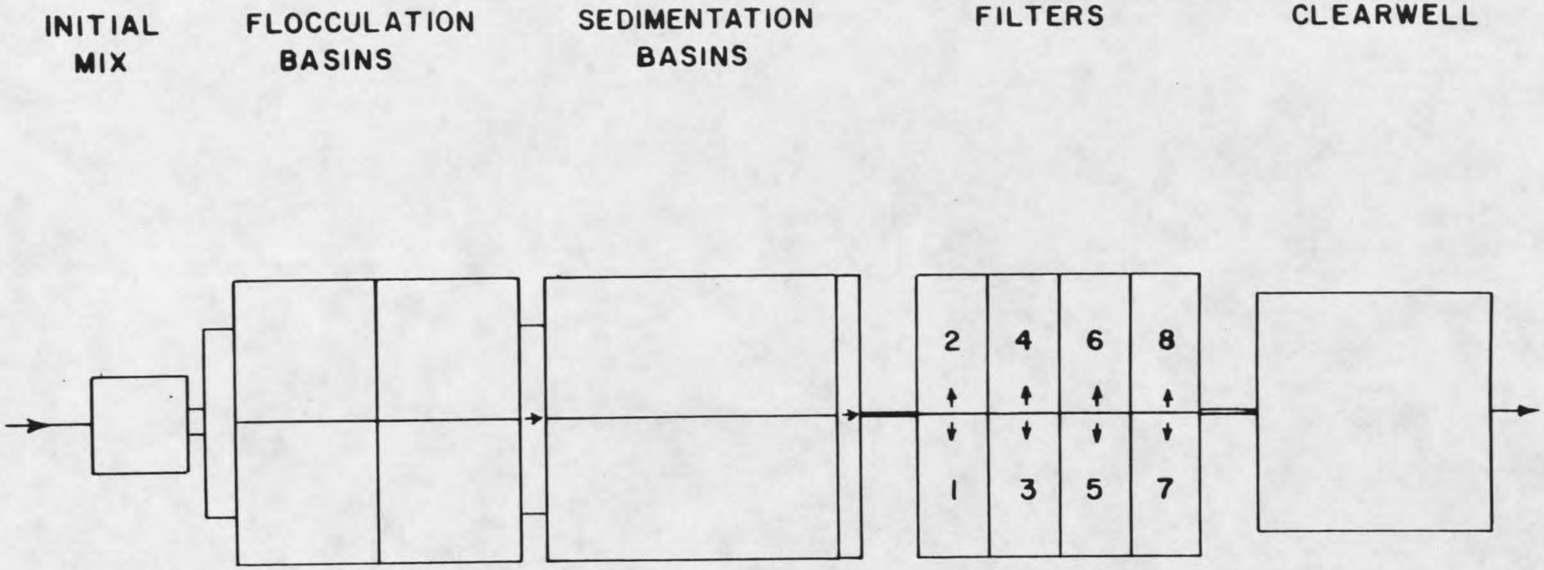

Figure 9. Layout of Missouri River Conventional Water Treatment Plant, Helena.

the water entering the distribution system. Contact time for chlorine is about 2 hours, depending on flow rate.

During periods of high municipal demand, the Helena water supplies are augmented by two other water sources. These are; Ten Mile Creek, which is chlorinated and enters the Helena distribution system, and the Eureka infiltration gallery, which is also chlorinated prior to entering the Helena distribution system. In addition, the Orophino line, an underground creek, which sometimes surfaces, is a year-round supply to some of the residences. The water is chlorinated, and enters a distribution system which is separate from the Helena system (Figure 10).

The HWTP receives its raw water supply via a pipeline and reservoir system. Water is pumped from the Missouri River, at Canyon Ferry Dam, through a 3 mile pipeline, and an approximately 7 or 8 mile canal to the Helena Valley Reservoir. The reservoir is mainly used for irrigation in the Helena Valley. It is protected from livestock, and human access is limited to fishing from non-motorized boats or from shore. Water is then pumped through another pipeline, 7 miles, to the water treatment plant (Figure 11). The reservoir seems to moderate any annual turbidity variations which there might be in the raw water itself. The raw water turbidities are consistently between 2 and 4 ntu's.

The distinguishing feature of the raw water at this water treatment plant is the growth of algae in the reservoir, sometimes causing a severe taste and odor problem in the late summer and early fall (Helena, City of, 1983). Potassium permagnate ($KMnO_4$) is applied to the raw water in the pipeline as it leaves the reservoir, in an effort to

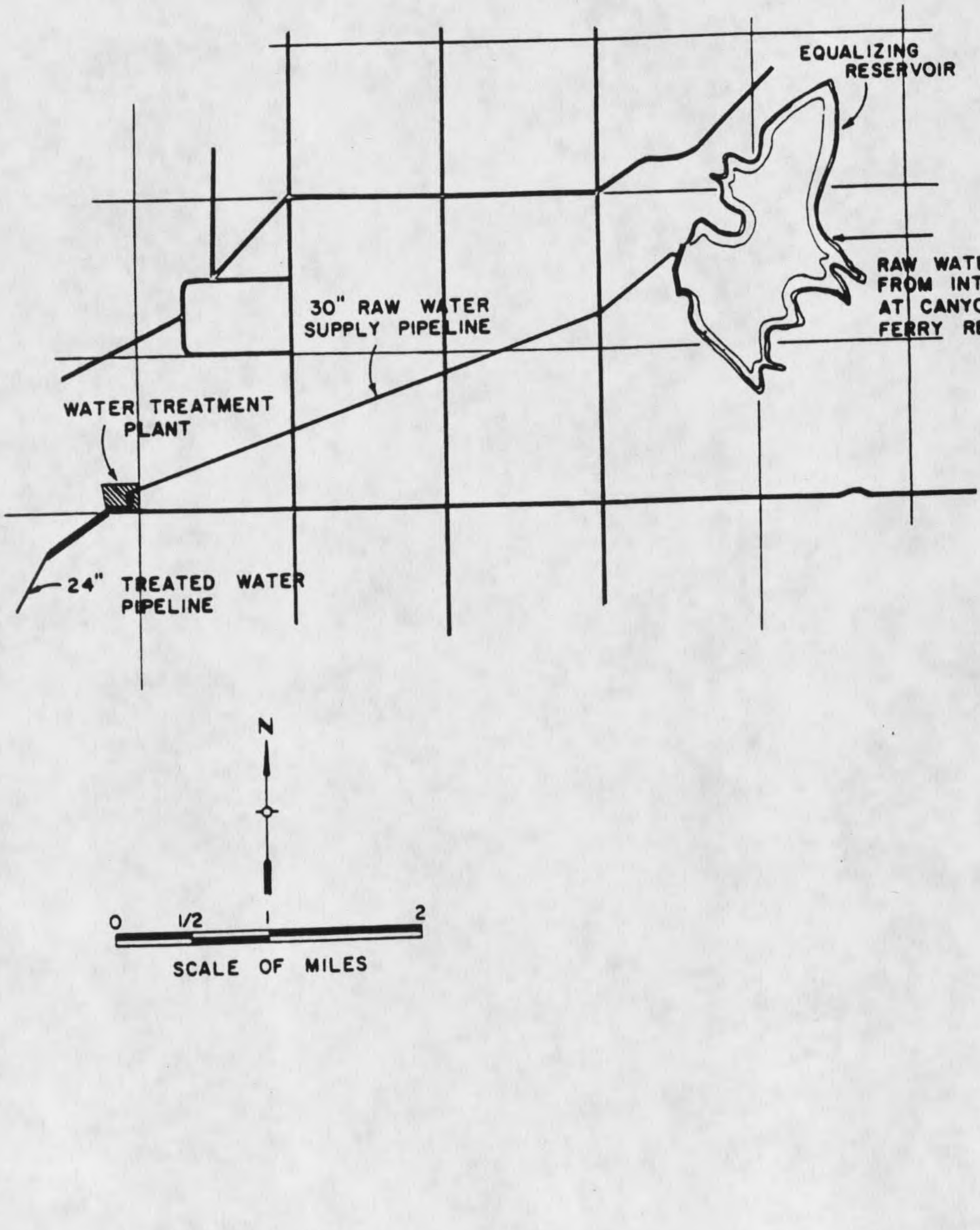

Figure 10. Distribution system. City of Helena.

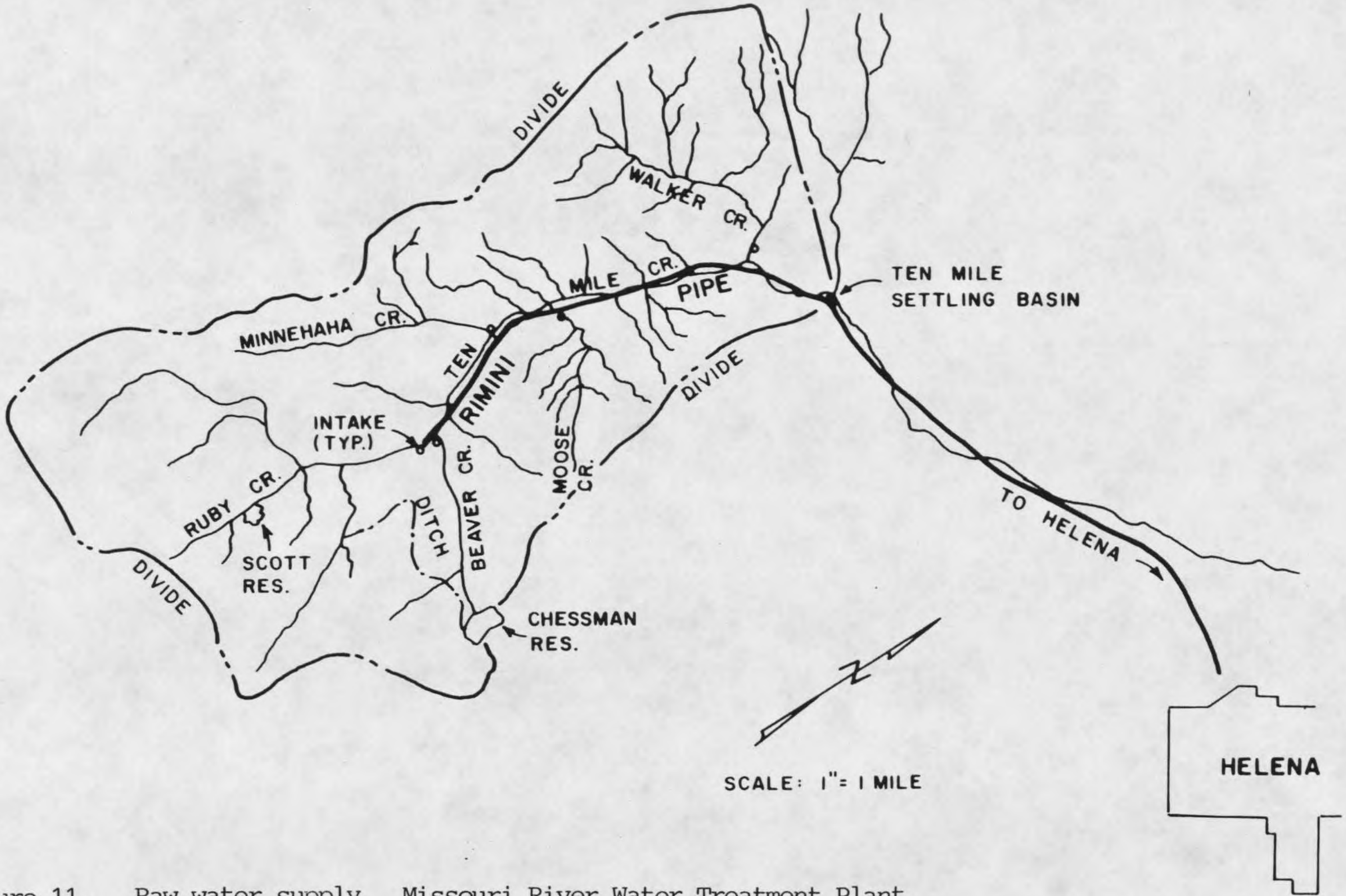

Figure 11. Raw water supply. Missouri River Water Treatment Plant, Helena.

control the problem. The estimated travel time for the water to reach the water treatment plant is 2.5 hours.

During the study period for this research, the algae did appear, and caused problems for the treatment facility in terms of taste and odor episodes. Application rates of powdered activated carbon (PAC) were as high as 1440 lb/24 hr. Concentrations of PAC applied reached as high as 78 mg/1 at the peak of the problem in late September. Because the municipal demand slowed in November 1986, the plant was shut down, and the city's alternative water sources were used as the primary water supplies. This decision was made by the city council, and approved by the Montana Water Quality Bureau, due to the high cost of treatment of the Missouri River water because of the large amounts of PAC required. By mid-December 1986, the plant was back on line, although only for short (4-5 hrs) periods of time.

Backwashing Procedures

Although similar in that they both have eight dual media filters, the BWTP and the HWTP have different backwash protocols. The backwash procedure for the BWTP is automatically initiated when a certain headloss is reached through the filter. The backwash cycle is a digitally programmed procedure. The sequence is described in Table 4.

Once the filter is put back on line, the filter effluent is filtered-to-waste for exactly 4.0 minutes. At this time, the valve to the clearwell, or, the "filter-to-keep" valve, opens from 4.0 to 4.5 minutes after backwash. From 4.5 to 5.0 minutes, the filter-to-waste valve closes. It is important to note that as the valve which leads to the clearwell opens, it first opens 100%, then slowly closes until the proper flowrate is reached, equalizing the head through the filter. By 5.0 minutes after the backwash, that is, 5.0 minutes into the filter run, the filter-to-waste valve is completely closed, and the clear well valve is open to a constant flow.

Table 4. Bozeman Water Treatment Plant Digitally Controlled Filter Backwash Procedure.

Time (min.)	Operation
0.0 - 8.0	Draw Down
8.00 - 11.20	Stand
11.20 - 17.40	Surface Wash
13.35	Backwash Pump On
14.05 - 27.55	Backwash at 11 gpm/ft^2 (2500 gpm)

The HWTP uses a manually initiated backwash, based on the headloss through the filters. The treatment plant operators control the length of the backwash, the flowrates used during the procedure, and the number and length of incremental startups and shutdowns of the backwash water flows. Since the procedure is operator controlled, there is quite a bit of variation between each backwash, as initiated and controlled by different operators. The protocol is described in Table 5.

In addition, the operators control the flowrates at which the filter is put back on line after the backwash. The standard operating procedure used for putting the filters back on line following a backwash is to incrementally increase the flowrate, until the operating flowrate is reached. This process usually takes 10-15 minutes, although the actual time varies depending upon the operator.

Table 5. Helena Missouri River Water Treatment Plant Manually Controlled Filter Backwash Procedure.

SEQUENCE OF EVENTS

1. Close the filter influent valve, lowering the water to the top of the surface wash pipe (Drawdown).
2. Close filter effluent valve.
3. Waste remaining water in filter basin.
4. Open surface wash valve.
5. Start backwash pump.
6. Open backwash valve slowly, 5 - 10 minute process.
7. At 1000 gpm backwash flow rate, shut surface wash valve.
8. Increase the backwash flow rate at 500 gpm increments untilreaching 3500 gpm flowrate in winter (13 gpm/ft^2), and 4000 gpm flowrate (15 gpm/ft^2) in summer.
9. Backwash at these rates for 4 minutes.
10. Open surface wash for 2 minutes, then close.
11. Close backwash valve in 500 gpm increments until closed.
12. Put filter back on line.

Again, as is the case with the backwash procedure, the operators use their own discretion for the actual lengths of time and flowrates used at each increment during the start of a filter run.

For this study, the operators were first asked to use the normal backwash procedure, including the incremental startup of the filter flows following the backwash. Later, they were asked to backwash the filters according to the standard procedure, but to start the filter back on line at 100% flow rate for that filter run, ie. a non-incremental startup.

Sampling Points

Water samples were collected from the raw water, flocculated water, individual filter effluents and plant (combined filter) effluent. At the BWTP, all sample points were accessible, and no modifications for sampling purposes were required. At the HWTP, sample spigots were installed by the City of Helena, at the base of each filter. Other accesses for sampling were already in place.

Both facilities use continuous monitoring of the plant raw water and effluent turbidities. The BWTP uses eight Hach Low Range 1720B Continuous flow turbidimeters, each monitoring one filter's effluent turbidity. A Hach Surface Scatter 5 Continuous Turbidimeter monitors the raw water turbidity. The plant effluent, or the combined filter effluent as it leaves the clearwell is monitored only by means of grab samples, taken once every four hours by the plant operators. These grab samples are analyzed using the BWTP laboratory Hach 2100 Turbidimeter.

The BWTP's continuous monitoring of each of the eight individual filter effluent turbidities is recorded on continuous strip charts. The raw water turbidity is, likewise, continuously recorded on a strip chart.

Samples taken for this study were analyzed for turbidity using the BWTP laboratory Hach 2100A Turbidimeter. This turbidimeter is exactly the same make and model as the turbidimeter which is used at the HWTP and of the turbidimeter which is available at the Montana State University (MSU) Environmental Engineering Laboratory. All three turbidimeters were tested at the outset of the research to determine the relative turbidity readings on each using the same sample of water (Table 6). The comparison was excellent, with almost no difference between the BWTP and HWTP turbidity readings, and a slightly variable turbidity reading when the HWTP and BWTP turbidity readings were compared against the MSU lab's turbidity readings. The explanation most likely is that the MSU turbidity standards, provided by the Hach company, were at least three years old, while the BWTP replaces their turbidity standards every six months and the HWTP replaces their turbidity standards annually. The MSU turbidimeter was not generally used in the data reported for this study.

Table 6. Comparison of the Hach 2100A Turbidimeters; BWTP, HWTP, MSU (March 26 and 27, 1986)

	Filter Influent, ntu	Filter Effluent, ntu
BWTP	2.5	0.22
	2.5	0.21
MSU	2.3	0.21
	2.2	0.19
HWTP	2.5	0.21
	2.4	0.21
MSU	2.3	0.20
	2.3	0.19

The HWTP monitors the combined filter effluents, ie. the plant clear well effluent, continuously, using a Hach Low Range Continuous 1720B

Turbidimeter. The readings from this turbidimeter are continuously recorded on a strip chart. The raw water influent to the water treatment plant is also continuously monitored and recorded, with a Hach Surface Scatter 5 Turbidimeter.

Since the filter effluent from each individual filter was not being monitored, the City of Helena agreed to help us with the necessary modifications for the research. As mentioned above, sample spigots were installed at the base of each filter for the purpose of gathering water samples. A Hach Low Range 1720B Continuous Turbidimeter was used, along with a Rustrak model #228 continuous recorder with strip charts. The turbidimeter and recorder were housed on a mobile stand, which could be used to monitor the filter effluent of any of the eight filters at the plant.

Neither water treatment plant samples for bacterial counts. Both cities have separate treatment plant and distribution system operations and maintenance. Coliform counts are taken by the distribution system staff at various points in the distribution system.

Experimental Methods

Turbidity

Turbidity samples were collected at both plants from raw water, filter influent, filter effluent and plant, or combined filter effluent. All samples were collected as grab samples, and read within one hour of collection, although usually much sooner, using the water treatment plant's laboratory turbidimeter. Grab samples for raw water, filter influent and plant effluent were usually taken once per filter run investigated. The grab samples collected gave good agreement with the continuously monitored and recorded turbidities. In the rare instances where the grab sample did not seem to agree with the continuous reading, a duplicate grab sample was taken. All grab samples were collected according to Standard Methods, by letting the open tap run to waste for 2 to 3 minutes.

The filter effluent samples were collected over time. Samples were collected prior to backwash, intermittently, usually every 10 to 15 minutes. This was done as a control. Immediately following backwash, grab samples were taken from the filter effluent according to the schedule described in Table 7. (See Figure 12 also.)

Table 7. Turbidity Sampling Schedule.

Time Elapsed After Backwash (min)	Frequency of Grab Sampling
0 - 15	1 sample every 30 s
15 - 25	1 sample every 1 min
30 - 60	1 sample every 10 min
60 - end of run	1 sample every hour

Microbiological

Microbiological samples were collected from the same sample points as the turbidity samples. Samples were collected, stored, transported and analyzed according to Standard Methods. Samples of the raw water and

BOZEMAN WATER TREATMENT PLANT TURBIDITY DATA

Date:______

Operator:________

Time Backwash was Initiated:______ Filter Number:______

Sample Time	Turbidity
t=0 (_____pm/am)....	______
0.5	______
1.0	______
1.5	______
2.0	______
2.5	______
3.0	______
3.5	______
4.0	______
4.5	______
5.0	______
5.5	______
6.0	______
6.5	______
7.0	______
7.5	______
8.0	______
8.5	______
9.0	______
9.5	______
10	______
11	______
12	______
13	______
14	______
15	______
16	______
17	______
18	______
19	______
20	______
25	______
30	______
40	______
50	______
60	______
2 hr	______
3 hr	______
4 hr	______
5 hr	______
6 hr	______
7 hr	______
8 hr	______
9 hr	______
10hr	______
11hr	______
etc................	______

Any other filters backwash during this time period, or any occurrance affecting flow or turbidity?

FILTER #	TIME OF B.W. (Beg. & End)
______	______

Figure 12. Data Sheet Used in Collection of Turbidity Data.

influent water to the filter were taken as well as the filter effluent over time after backwash. Sample times for the post backwash period are described in Table 8.

Table 8. Microbiological Sampling Schedule.

BWTP	HWTP
(Time after Backwash)	
0 min	0 min
2.5	2.5
4.5	5.0
5.0	7.5
7.5	10.0
10.0	12.5
15.0	15.0
20	20
30 min	30 min
1 hour	1 hour
2 hour	2 hour
3 hour	3 hour
4 hour	4 hour

Water samples were collected in clean 1 Liter and 500 mL Nalgene sample bottles. The bottles were prepared for use by washing with hot tap water and soap, rinsed 15 times with hot tap water, then rinsed 3 times with hot sterile (autoclaved at 251 F for 15 min.) deionized water. The sample bottles contained 5 ml/l of a 10% solution of sodium thiosulfate, (J.T. Baker Chemical Co.; 5-Hydrate Crystal; $Na_2S_2O_3$ $5H_2O$), prepared aseptically with sterile deionized water. After collection of samples, the bottles were kept on ice at 4 to 6 C for not more than 36 hours before plating.

Heterotrophic plate counts were made, as well as total coliform counts. Heterotrophic plate counts were made on standard plate count agar (Difco DF-0479-02-0), by the spread plate method. This method was chosen over the pour plate method, due to the temperature shock which could affect the organisms, due to the temperature of the water samples averaging less than 10 C when collected. Samples were stored at temperatures of 4 to 6 C for no longer than 24 hours, including transport, prior to plating. All samples were plated in triplicate. Dilutions were unnecessary because of the low numbers of organisms usually present in the samples. Triplicate sample sizes plated were: 0.1, 0.5 and 1.0 mL, after backwash, and 0.05, 0.1 and 0.5 mL for the raw water. Plates were incubated at 32.5 C for 24, 48 and 72 hours, and were counted using a colony counter. Control plates were incubated simultaneously. Total coliforms were enumerated by three methods:

1) Most Probable Number Method (MPN)
2) Membrane Filtration, using m-Endo LES agar
3) Membrane Filtration, using MT-7 agar

The MPN method of enumeration was used as a supplement to, and in order to verify, results of the membrane filtration method. This method was only used once per each season. These results were considered as a statistical control.

Membrane filtration, with m-Endo LES agar (Difco DF-0736-01) is probably more commonly used than the MPN method for the detection of total coliforms in drinking water. This method provides comparability with other studies, and since it is the standard method most often used, it gives a picture of total coliforms, as would be seen by the operators of the water treatment plant, or by a regulatory body.

Membrane filtration with MT-7 agar (Difco DF-0018-15-3) was used in order to assess the numbers of injured coliforms present in the drinking water over various stages of the post backwash period. The common practice of prechlorination (used by the HWTP), and the use of chlorinated backwash water, (both HWTP and BWTP), increases the likelihood of chlorine injured organisms being present in the filter effluent. In contrast, many of the pilot scale studies in the literature which were carried out to determine the relationship between turbidity and bacterial numbers in the post backwash period of a filter utilize dechlorinated backwash water for their studies. The MT-7 agar was used in hopes of gaining a "truer" picture of the bacterial numbers in the post backwash filter effluent under actual treatment plant conditions (ie. chlorinated backwash water).

All membrane filtration was done according to Standard Methods. Millipore 250 mL filtration units were used with Schleicher & Schwell, Inc. (47 mm, 0.45 um) membrane filters. All rinse water and controls were sterile deionized water. Total coliform plates were incubated at 32.5 C for 24 hours, and were incubated for an additional 24 hours to determine if any more colonies appeared.

Seasonal Considerations

A significant portion of this study was to determine what effect, if any, seasonal variations played in the filter effluent quality, especially during the period immediately following a backwash. Montana has four very definite seasons, and the raw water quality varies with those seasons. Weather conditions were recorded on each day that a filter run was to be observed. Raw water parameters such as temperature, turbidity, and pH were monitored on a daily basis.

As in the case of turbidity, pH measurements were made using the instruments available at the water treatment plants. The BWTP uses an Orion Research model 701A / digital ion pH meter. The HWTP uses a Corning model #125 pH meter. Standards were utilized; each plant has on hand, and uses, standardized pH solutions, which are bought from the manufacturers. The BWTP uses VWR Scientific green pH 7.0 buffer solution, and the HWTP uses pH 7.0 and 10.0 Biophram standard solutions.

Weather conditions were recorded at the BWTP on a daily basis. The conditions noted were temperature (maximum and minimum), precipitation (inches, and form), wind speed (variation in mph), and general observations on cloud cover, etc.. The HWTP does not record weather conditions on a regular basis. However, the operators were requested to record some general weather observations on the days during which samples were taken.

Fluoride and Chlorine Tracer Studies

One of the objectives of this study was to determine the characteristics of the post backwash period, and its association with the backwash water remnants. In order to do this, experiments were conducted using "tracers" of fluoride and chlorine, much as a dye tracer would be conducted in a pilot scale context.

The chlorine tracer was conducted at the BWTP, taking advantage of the fact that the BWTP does not pre-chlorinate the raw water. Thus, following a backwash, the first few minutes of the filter effluent would have a chlorine concentration in direct proportion to the backwash water remnants.

Samples for the chlorine tracer studies were taken in exactly the same manner as turbidity samples. The samples were kept cold, and read less than 60 minutes after collection. Concentrations were determined, using Hach Free Chlorine Reagent Pillows (CAT. 21055) and the BWTP's Bausch & Lomb Spectronic 20 model spectrophotometer,at 530 nm wavelengths. Absorbance was read, and converted to mg/L using the equation of the slope: $y = mx + b$, where y = absorbance, m = slope = 0.213, x = Cl_2 residual (mg/L), and $b = 0$.

Fluoride was also used as a tracer. The fluoride tracer was used in the reverse of the chlorine tracer. That is, the fluoride was added to the influent water to the filter, in contrast to chlorine which was an indicator of the backwash water remnants.

Sodium silicofluoride (Na_2SiFl_6) is the form of fluoride used at the BWTP as a fluoride supplement to the Bozeman water supply. This chemical is in powdered form. In order to use it as a tracer, the Na_2SiF_6 was mixed with water, to reach a maximum concentration. This concentration varied, according to the ambient temperature within the plant (Table 9). Prior to beginning the experiment, samples were taken of the filter effluent, to determine the background levels of naturally occurring fluoride.

Table 9. Soluability of Sodiumsilicofluoride in Water.

Temperature (C)	Solubility
0	0.44 g / 100 g H_2O
100	2.45 g / 100 g H_2O

The fluoride tracer solution was added to the filter influent immediately following the backwash. The solution was pumped into the filter influent at a constant rate, measured, prior to the experiment using 2L graduated cylinders and a stopwatch. The pump rate was checked periodically throughout the tracer experiment. Samples were taken in the same manner as for the turbidity samples from the filter effluent over time. The collected samples were warmed to 20 C in a water bath, then analyzed for Fl^-, using Hach Spandns Reagent (hydrochloric acid and inorganic arsenic, CAT.444) with the BWTP Bausch and Lomb Spectronic 20 spectrophotometer (580 nm). Percent transmittance was converted to concentration in mg/L (Figure 13). All samples were analyzed within one hour of collection.

Procedure Group 1 – Bausch and Lomb Spectronic 20 and 21 (1-inch test tube)

a. Adjust the Wavelength control to 580 nm.

b. With the sample compartment of the Spectronic 20 empty, or using an opaque rod in the Spectronic 21, cover the sample compartment and adjust the Zero control for a reading of zero %T.

c. Place 1-inch test tube containing treated fluoride standard into the sample compartment and cover the compartment. Adjust the Full Scale control for a % T reading appropriate for the fluoride standard used. Refer to the tables below.

d. Place a 1-inch test tube containing the treated water sample to be tested into the sample compartment, cover the compartment and read the percent transmittance. Refer to the following tables to determine the mg/L fluoride (F).

Concentration vs. % Transmittance

%T	%T Units									
Tens	0	1	2	3	4	5	6	7	8	9
10										
20		.01	.07	.12	.17	.22.	26.	31.	35	.39
30	.43	.47	.51	.55	.58	.62	.65	.69	.72	.75
40	.78	.81	.84	.87	.90	.92	.95	.98	1.00	1.03
50	1.05	1.08	1.10	1.12	1.14	1.17	1.19	1.21	1.23	1.25
60	1.27	1.29	1.31	1.33	1.35	.137	1.39	1.41	1.43	1.44
70	1.46	1.48	1.49	1.51	1.53	1.54	1.56	1.58	1.59	1.61
80	1.63	1.65	1.66	1.68	1.70	1.72	1.73	1.75	1.77	1.78
90	1.80	1.82	1.84	1.86	1.88	1.90	1.92	1.94	1.96	1.98

Bausch and Lomb Spectronic 20

Figure 13. Fluoride Concentration Determination.

CHAPTER 5

RESULTS AND DISCUSSION

The results indicate that the initial stages of filter effluent from a backwashed filter show higher turbidity and particle counts than the effluent later in the filter run. Bacterial counts were variable. The magnitude and duration of the initial degradation turbidity components; (1) vary seasonally, (2) vary from treatment plant to treatment plant, (3) depend upon flowrate, and (4) to a lesser extent, depend upon the raw water turbidities.

Turbidity

The initial effluent from backwashed filters showed turbidity readings higher than were experienced later in the filter run. This characteristic occurred at both water treatment plants. This finding is not unexpected, as any water treatment plant operator would report such results. However, the characteristic turbidity profiles, over time, varied; (1) between the BWTP and the HWTP, (2) seasonally, at the BWTP, and (3) is dependent upon flowrate.

In addition, a dual peak characteristic was observed quite readily at the BWTP, while the HWTP's characteristic turbidity profile seemed to show a mild dual peak characteristic.

Bozeman Water Treatment Plant

Thirty filter runs were studied at the BWTP (Table 10). The BWTP turbidities after backwash over time showed a characteristic turbidity profile. This profile was evident during the springtime, summer and fall. A winter profile which differed from the characteristic profile, was observed in mid-winter (Figure 14).

The characteristic profile occurred when flowrates ranged from 1.9 gpm/ft^2 to 4.7 gpm/ft^2 (Filter runs #1 - #26). There seems to be three peaks, one occurring at between 1 and 2.5 minutes, the second at 4 to 5 minutes, and the third at 7 to 22 minutes, whereupon the turbidities tend to decrease (Figure 15).

The first turbidity peak was quite small, in comparison with the following two peaks. This turbidity peak tended to grow in relationship to the other turbidity peaks over the seasons, as the year progressed. In the late fall and winter, this peak became much more noticeable. Average magnitude, over the entire year was 0.37 ntu. The magnitude of all turbidity peaks is calculated as the difference between the peak turbidity, and the ambient, or background turbidity which that filter reaches and maintains later in the filter run.

The second turbidity peak is spike shaped. This peak was quite noticeable during the spring and summer, and shrank as the flowrates through the filter decreased. This peak ranged from 0.20 ntu to 1.0 ntu in magnitude, averaging 0.55 ntu.

The third turbidity peak is large, in terms of duration and magnitude. This turbidity peak averaged 4.9 hours in length and 0.60

Table 10. Summary of Filter Runs at the Bozeman Water Treatment Plant. Experimental Results.

Run No.	Filter No.	Date of Run	Plant Influent			Plant Effluent			Chemical Additions (mg/L)		Cl Resid. (mg/L) (final)	Flow Rate (gpm/ sq ft)	Det. Time to Influent, T_d, (min)
			Temp. °C	pH	Turb. ntu	Temp. °C	pH	Turb. ntu	Bento-nite	Cationic Polymer			
1	2	3-28-86	6.0	6.2	4.10	4.0	6.0	0.17	1.49	3.99	1.33	1.9	21.9
2	2	4-03-86	6.0	6.4	7.00	5.0	6.3	0.37	2.81	5.36	1.74	1.9	21.9
3	2	4-14-86	4.0	6.8	6.20	5.0	6.7	0.21	2.34	3.41	1.70	2.8	14.9
1	4	4-29-86	3.0	6.2	5.40	3.0	6.1	0.20	2.65	4.90	1.64	2.7	15.5
2	4	5-07-86	4.0	6.2	7.90	4.0	6.0	0.20	3.49	5.72	1.41	1.9	21.9
3	4	6-01-86	10.0	6.2	7.50	10.0	6.2	0.17	0.91	3.40	1.45	3.5	11.9
4	4	6-03-86	8.0	6.4	6.50	8.0	6.3	0.35	0.86	2.71	1.55	3.6	11.6
5	4	6-04-86	10.0	6.1	6.10	10.0	6.0	0.24	1.06	2.66	1.58	3.7	11.3
6	4	6-11-86	8.0	6.3	7.90	9.0	6.0	0.23	0.32	3.40	1.51	3.7	11.3
7	4	6-14-86	9.0	6.2	4.70	10.0	6.1	0.21	0.33	3.13	1.80	3.2	13.1
8	4	6-15-86	13.0	6.8	5.00	13.0	6.7	0.67	0.55	3.79	1.74	3.6	11.6
9	4	6-16-86	10.0	6.2	3.80	10.0	6.1	0.35	1.05	3.23	1.60	3.1	13.5
10	4	6-23-86	11.0	6.4	2.00	12.0	6.5	0.59	1.15	3.05	1.60	3.9	10.7
11	4	7-08-86	13.0	6.3	0.87	12.0	6.2	0.20	2.72	3.90	1.38	3.8	11.0
12	4	7-23-86	12.0	6.5	1.35	11.0	6.3	0.39	1.69	4.22	1.34	4.6	9.1
13	4	8-01-86	13.0	6.7	0.90	13.0	6.5	0.34	2.58	4.30	1.56	4.5	9.3
14	4	9-28-86	7.0	7.1	0.90	7.0	7.0	0.37	4.29	3.87	1.55	4.7	8.9
15	4	10-05-86	9.0	7.2	0.98	8.0	7.2	0.16	5.47	3.65	1.60	3.0	13.9
16	4	10-12-86	3.0	6.6	0.67	3.0	6.7	0.21	5.19	3.92	1.46	2.9	14.4
17	4	10-22-86	3.0	6.5	1.50	4.0	6.7	0.20	3.23	3.23	1.41	3.0	13.9
18	4	10-24-86	4.0	6.8	0.63	4.0	6.9	0.19	3.12	3.01	1.46	3.0	13.9
19	4	11-01-86	3.0	7.0	0.63	4.0	7.2	0.19	3.81	3.07	1.42	3.3	12.7
20	4	11-04-86	3.0	7.3	0.84	3.0	7.1	0.29	2.96	3.14	1.31	3.1	13.5

Table 10. (Continued.)

Run No.	Filter No.	Date of Run	Plant Influent			Plant Effluent			Chemical Additions (mg/L)		Cl Resid. (mg/L) (final)	Flow Rate (gpm/ sq ft)	Det. Time to Influent, T_d, (min)
			Temp. °C	pH	Turb. ntu	Temp. °C	pH	Turb. ntu	Bento-nite	Cationic Polymer			
21	4	11-06-86	2.0	6.9	0.75	3.0	6.7	0.24	2.82	2.96	1.45	3.2	13.1
22	4	11-16-86	2.0	7.0	0.85	2.0	7.0	0.20	3.53	3.10	1.10	3.2	13.1
23	4	11-19-86	2.0	6.7	2.20	2.0	6.4	0.28	3.37	2.95	1.00	3.0	13.9
24	4	12-16-86	2.0	7.0	0.60	2.0	6.8	0.16	3.69	1.84	1.10	3.0	13.9
25	4	12-23-86	1.0	6.6	0.88	1.0	6.2	0.21	3.22	1.89	1.34	3.0	13.9
26	4	12-27-86	1.0	7.0	0.87	1.0	6.4	0.13	2.51	1.94	1.16	3.9	10.7
27	4	1-14-87	1.0	6.5	0.65	1.0	6.4	0.08	2.06	1.43	1.55	1.7	24.6
28	4	1-17-87	0.0	6.4	0.83	0.0	6.1	0.09	2.14	1.49	1.22	1.6	26.1
29	4	1-23-87	1.0	6.5	0.62	1.0	6.4	0.12	2.53	1.37	1.30	1.6	26.1
30	4	1-26-87	1.0	6.8	1.20	1.0	6.6	0.13	2.09	1.17	1.17	1.7	24.6
Mean		-	5.6	6.6	2.81	5.6	6.5	0.25	2.49	3.19	1.44	3.1	14.9
Maximum		-	13.0	7.3	7.90	13.0	7.2	0.67	5.47	5.72	1.80	4.7	26.1
Minimum		-	0.0	6.1	0.60	0.0	6.0	0.08	0.32	1.17	1.00	1.6	8.9
Standard Deviation		-	4.2	0.3	2.6	4.1	0.4	0.1				0.9	5.1

Note: 1 gpm/sq ft - 2.44 m/h

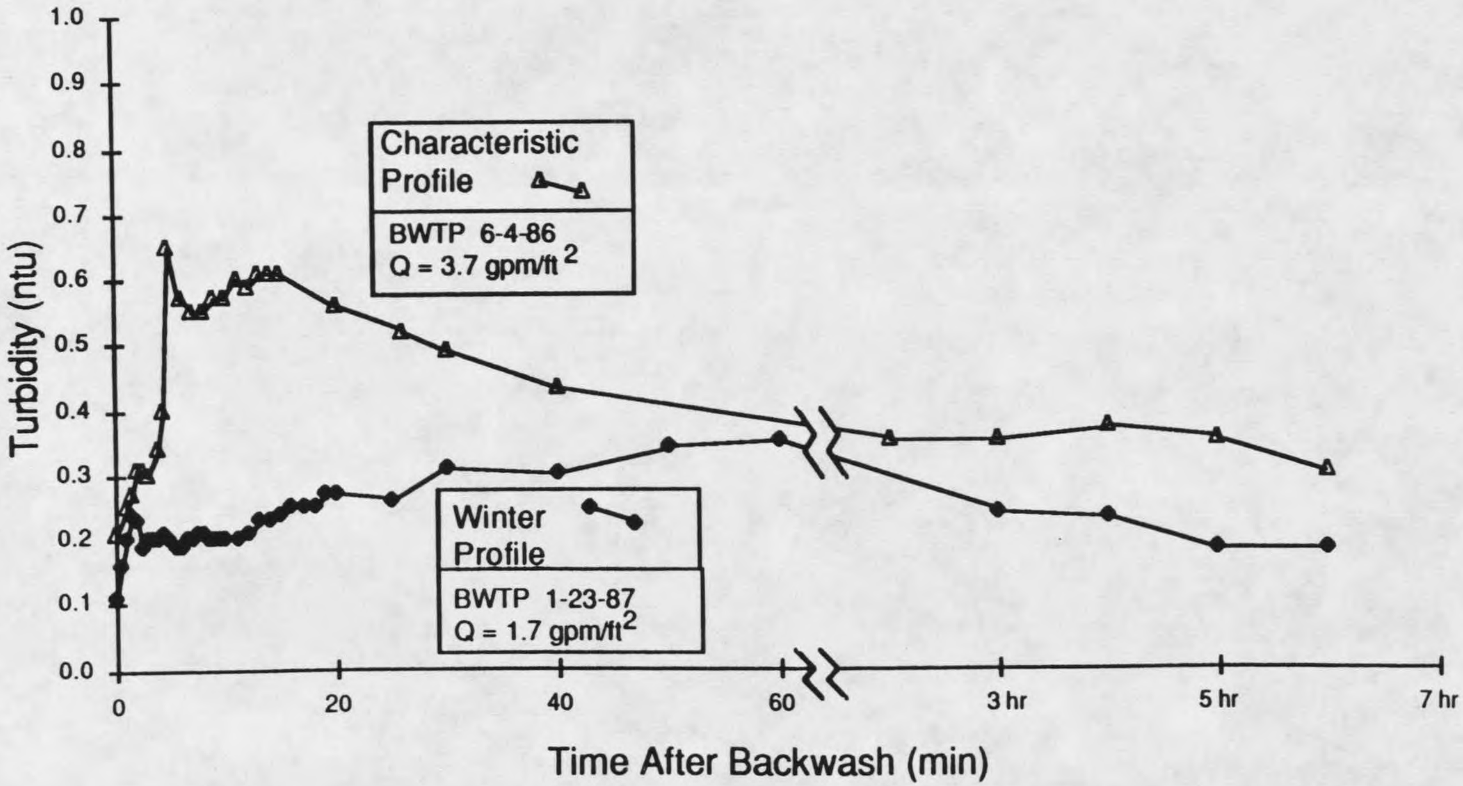

Figure 14. Characteristic BWTP Turbidity Profile Compared With the BWTP Mid-Winter Turbidity Profile.

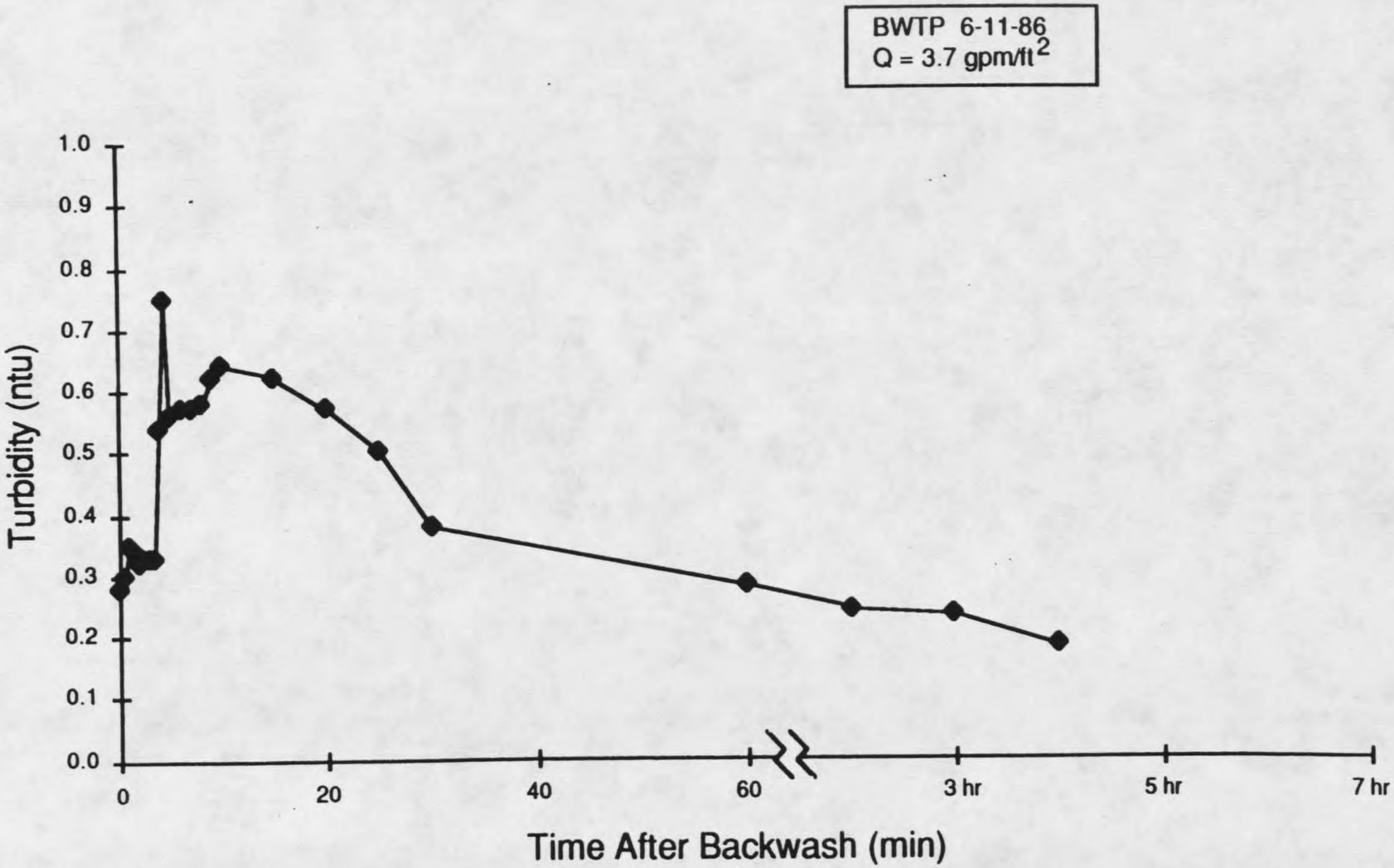

Figure 15. Characteristic Turbidity Profile: BWTP. Spring, Summer and Fall Seasons.

ntu in magnitude. The filter effluent turbidity upon recovery from the post backwash period averaged 0.25 ntu.

Figure 16, below, shows the turbidity profile at the BWTP during the winter. Flowrates were steady, from 1.6 gpm/ft^2 to 1.7 gpm/ft^2. From the figure, the trend towards a dual peaked post backwash turbidity profile is obvious. The first peak occurs at about 1 minute into the filter run, and the second, larger peak occurs about 25 minutes after backwash.

Table 11 lists each filter run, with the three turbidity peaks measured in terms of time at which the peak turbidity occurred, the maximum turbidity at that time, and the length of the period over which that peak occurred. Also included are the calculated detention times of the backwash water remnants up to the wash water gutter (T_d) for each flow rate (where $T_d = V/Q$).

It can be seen that the time at which the third turbidity peak occurs often is close to the calculated detention time through the filter. Thus, the detention time can be used to calculate when the highest turbidity will be recorded in the post backwash period. Also, this finding tends to support the idea that the initial degradation of the filter effluent is a function of the backwash water remnants through the filter unit. On the other hand, the detention times indicate the point at which the filter effluent begins to originate from the filter influent, rather than from the backwash water remnants. Following this line of thought, the largest peak in the initial degradation period is a function of the influent water.

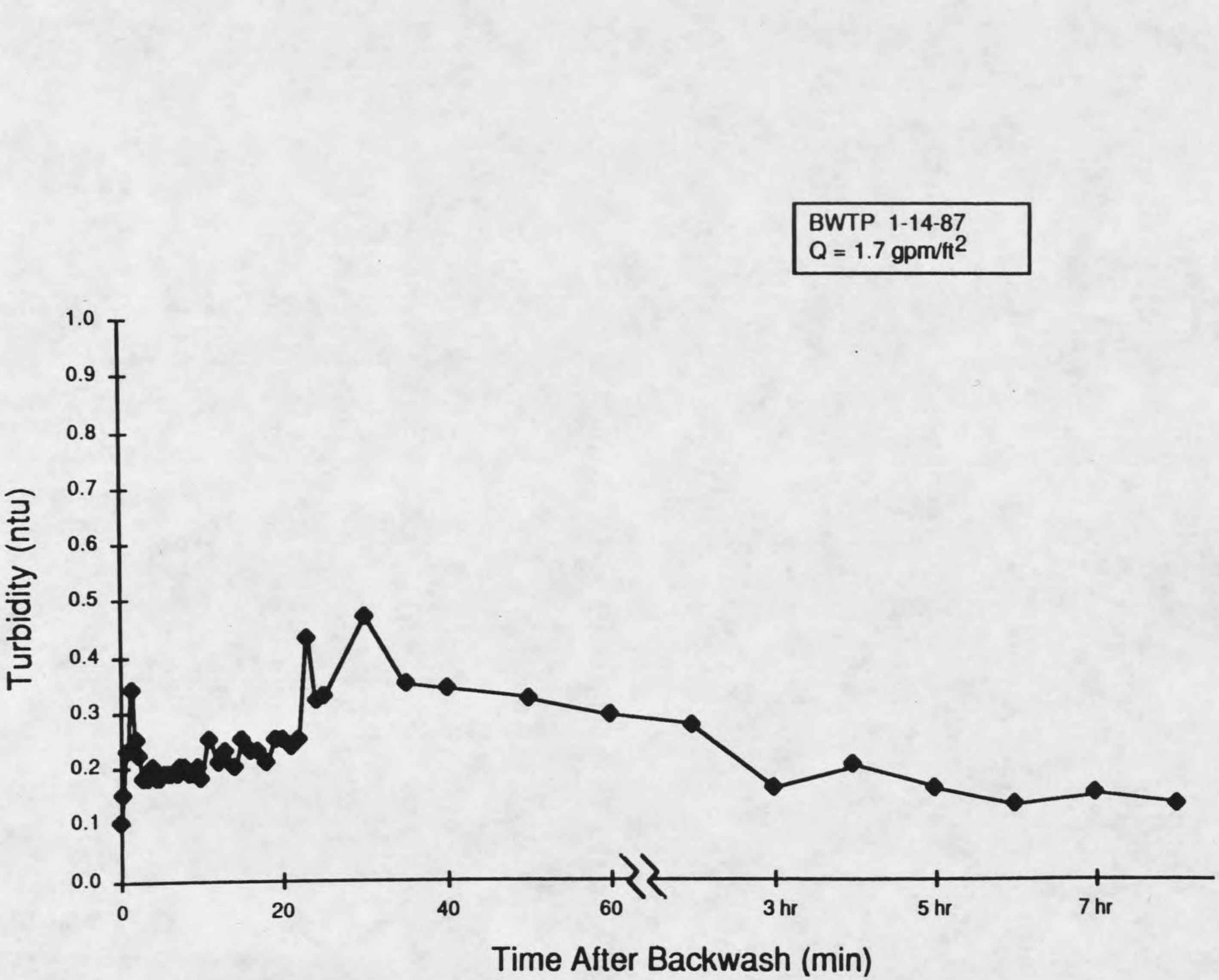

Figure 16. Winter Low Filtration Rate Turbidity Profile: BWTP.

Table 11. Turbidity Peaks From Bozeman Water Treatment Plant. Experimental Results.

Run No.	Filter No.	Date of Run	Flow Rate (gpm/sq ft)	Peak 1 Time (min)	Peak 1 Max. Turb. (ntu)	Peak 1 Duration (min)	Peak 2 Time (min)	Peak 2 Max. Turb. (ntu)	Peak 2 Duration (min)	Peak 3 Time (min)	Peak 3 Max. Turb. (ntu)	Peak 3 Duration (hr)	Det. Time to Influent, T_d, (min)
1	2	3-28-86	1.9	1.0	0.35	3.0	3.5	0.52	2.0	25	0.58	9.0	21.9
2	2	4-03-86	1.9	5.0	0.47	2.5	3.5	0.50	1.5	20	0.65	6.0	21.9
3	2	4-14-86	2.8	2.5	0.36	4.0	4.5	0.53	0.5	20	0.69	1.5	14.9
1	4	4-29-86	2.7	2.5	0.36	4.0	5.0	0.72	2.0	10	0.56	1.0	15.5
2	4	5-07-86	1.9	3.0	0.37	4.0	6.0	0.65	3.0	20	0.61	5.0	21.9
3	4	6-01-86	3.5	3.0	0.32	3.5	4.5	0.78	1.5	7	0.75	8.0	11.9
4	4	6-03-86	3.6	2.0	0.37	4.0	5.0	0.67	3.0	11	0.67	4.0	11.6
5	4	6-04-86	3.7	2.0	0.31	4.0	5.0	0.65	2.0	13	0.61	8.0	11.3
6	4	6-11-86	3.7	1.0	0.35	3.5	4.5	0.75	1.5	10	0.64	2.0	11.3
7	4	6-14-86	3.2	2.5	0.31	3.5	5.0	0.47	3.5	13	0.63	5.0	13.1
8	4	6-15-86	3.6	0.0	0.67	3.0	4.0	0.60	0.5	11	1.00	0.7	11.6
9	4	6-16-86	3.1	1.5	0.40	4.0	5.0	0.72	2.0	15	0.93	2.0	13.5
10	4	6-23-86	3.9	2.0	0.53	4.0	5.5	0.88	2.0	11	1.00	2.0	10.7
11	4	7-08-86	3.8	1.5	0.27	4.0	7.0	0.56	4.0	13	0.55	8.0	11.0
12	4	7-23-86	4.6	2.0	0.52	4.0	6.0	1.00	4.0	15	0.90	1.5	9.1
13	4	8-01-86	4.5	1.0	0.42	3.0	5.5	0.57	2.0	7	0.67	1.3	9.3
14	4	9-28-86	4.7	1.0	0.42	3.5	5.0	0.47	1.5	7	0.53	0.7	8.9
15	4	10-05-86	3.0	2.5	0.29	3.5	4.5	0.35	1.5	13	0.37	5.0	13.9
16	4	10-12-86	2.9	1.5	0.29	3.5	4.5	0.40	3.0	18	0.63	5.0	14.4
17	4	10-22-86	3.0	1.5	0.33	4.0	4.5	0.68	3.5	25	0.65	7.0	13.9
18	4	10-24-86	3.0	1.5	0.34	3.5	4.5	0.57	4.0	19	0.54	7.0	13.9
19	4	11-01-86	3.3	1.5	0.30	4.0	5.0	0.45	3.0	21	0.56	4.0	12.7
20	4	11-04-86	3.1	1.5	0.38	4.0	5.0	0.50	4.0	21	0.55	5.0	13.5

Table 11. (Continued.)

Run No.	Filter No.	Date of Run	Flow Rate (gpm/sq ft)	Peak 1 Time (min)	Peak 1 Max. Turb. (ntu)	Peak 1 Duration (min)	Peak 2 Time (min)	Peak 2 Max. Turb. (ntu)	Peak 2 Period (min)	Peak 3 Time (min)	Peak 3 Max. Turb. (ntu)	Peak 3 Duration (hr)	Det. Time to Influent, T_d, (min)
21	4	11-06-86	3.2	1.5	0.40	4.0	5.0	0.58	3.5	22	0.59	8.0	13.1
22	4	11-16-86	3.2	1.5	0.42	4.0	5.0	0.59	3.5	14	0.68	7.0	13.1
23	4	11-19-86	3.0	1.5	0.43	4.0	5.5	0.62	4.0	10	0.55	4.0	13.9
24	4	12-16-86	3.0	2.0	0.36	3.5	5.0	0.59	4.0	13	0.44	7.0	13.9
25	4	12-23-86	3.0	1.5	0.31	3.5	4.0	0.31	3.0	14	0.36	3.0	13.9
26	4	12-27-86	3.9	1.5	0.28	4.0	5.0	0.59	4.0	21	0.42	1.0	10.7
27	4	1-14-87	1.7	1.5	0.34	3.5	4.0	0.20	1.0	30	0.47	8.0	24.6
28	4	1-17-86	1.6	1.0	0.30	3.5	4.0	0.21	1.0	25	0.38	8.0	26.1
29	4	1-23-87	1.6	1.5	0.24	4.0	4.5	0.21	1.0	30	0.31	8.0	26.1
30	4	1-26-87	1.7	1.0	0.29	3.5	4.0	0.21	2.5	15	0.35	8.0	24.6
Mean		-	3.1	1.8	0.37	3.7	4.8	0.55	2.5	16	0.60	4.9	14.9
Maximum		-	4.7	5.0	0.67	4.0	7.0	1.00	4.0	30	1.00	9.0	26.1
Minimum		-	1.0	0.0	0.24	2.5	3.5	0.20	0.5	7	0.31	0.7	8.9
Standard Deviation		-	4.2	0.7	0.09	0.4	0.7	0.20	1.1	6	0.17	2.8	5.1
Filter No. 2 Mean		-	2.2	2.8	0.39	3.2	3.8	0.52	1.3	22	0.64	5.5	19.6
Filter No. 4 Mean		-	3.2	1.7	0.36	3.7	4.9	0.56	2.6	16	0.60	4.8	14.4

It can also be seen from this table that the two filters, filter #2, and filter #4, have similar characteristics, in terms of turbidity peaks during the post backwash period.

Filter runs #22 to #30 were considered winter season. Of these, runs #22 to #26 exhibited the "characteristic" post backwash turbidity profile which occurred during most of the year, while runs #27 to #30 had the lower turbidity profile, pictured in Figure 16. Referring to Table 10, the influent water characteristics during runs #22 to #26, and #27 to #30 were not dissimilar. Also, the weather recorded for these days was average Bozeman winter weather. What then caused the differences seen in the post backwash turbidity characteristics? That is, why would filter runs #22-#26 show the turbidity profile of the balance of the year, with three distinct turbidity peaks, while filter runs #27-#30 show a flatter shaped dual peaked characteristic?

The only major difference between these filter runs is the filter flowrate. The shape of the turbidity profile for a newly backwashed filter is dependent on the flowrate, all other parameters considered equal.

Table 12 breaks down the information of Table 11 by considering the filter runs with similar turbidity profile shapes. Also, filter #2 and filter #4 are considered separately. From this table Figures 17, 18 and 19 were drawn. These are theoretical turbidity profiles for the BWTP, based on information gathered in Table 12.

Table 13 is the same data, but broken down in terms of season. Flowrates are highest in the summer, as expected, and lowest in the

Table 12. Mean and Standard Deviation of Peak Turbidities By Shape of Profile.

Run No.	Filter No.	Flow Rate (gpm/sq ft)	Peak 1 Time (min)	Peak 1 Max. Turb. (ntu)	Peak 1 Duration (min)	Peak 2 Time (min)	Peak 2 Max. Turb. (ntu)	Peak 2 Duration (min)	Peak 3 Time (min)	Peak 3 Max. Turb. (ntu)	Peak 3 Duration (hr)
1-3	2										
Mean		= 2.2	1.3	0.39	3.2	3.8	0.52	1.3	21.7	0.64	5.5
Standard Deviation		= 0.5	1.0	0.07	0.76	0.56	0.02	0.76	2.9	0.06	3.8
1-26	4										
Mean		= 3.4	1.7	0.38	3.75	5.02	0.60	2.8	14.4	0.63	4.3
Standard Deviation		= 0.6	0.65	0.09	0.32	0.64	0.15	1.05	5.1	0.17	2.6
27-30	4										
Mean		= 1.65	1.25	0.29	3.6	4.13	0.21	1.4	25.0	0.38	8.0
Standard Deviation		= 0.06	0.29	0.04	0.25	0.25	0.01	0.75	7.1	0.07	0.0

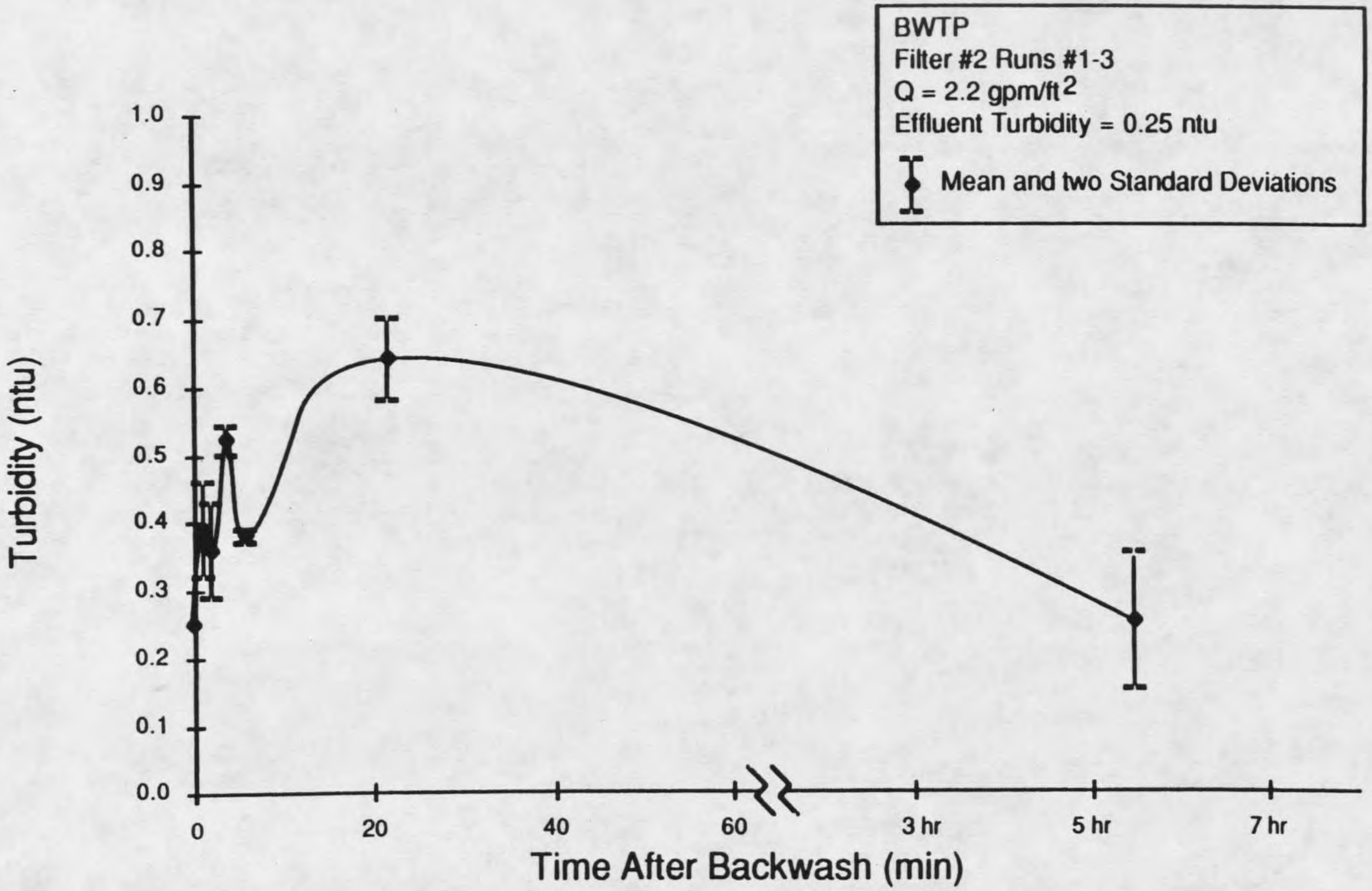

Figure 17. Mean Profile With Three Turbidity Peaks. Filter Runs No.1 to 3 on Filter No.2.

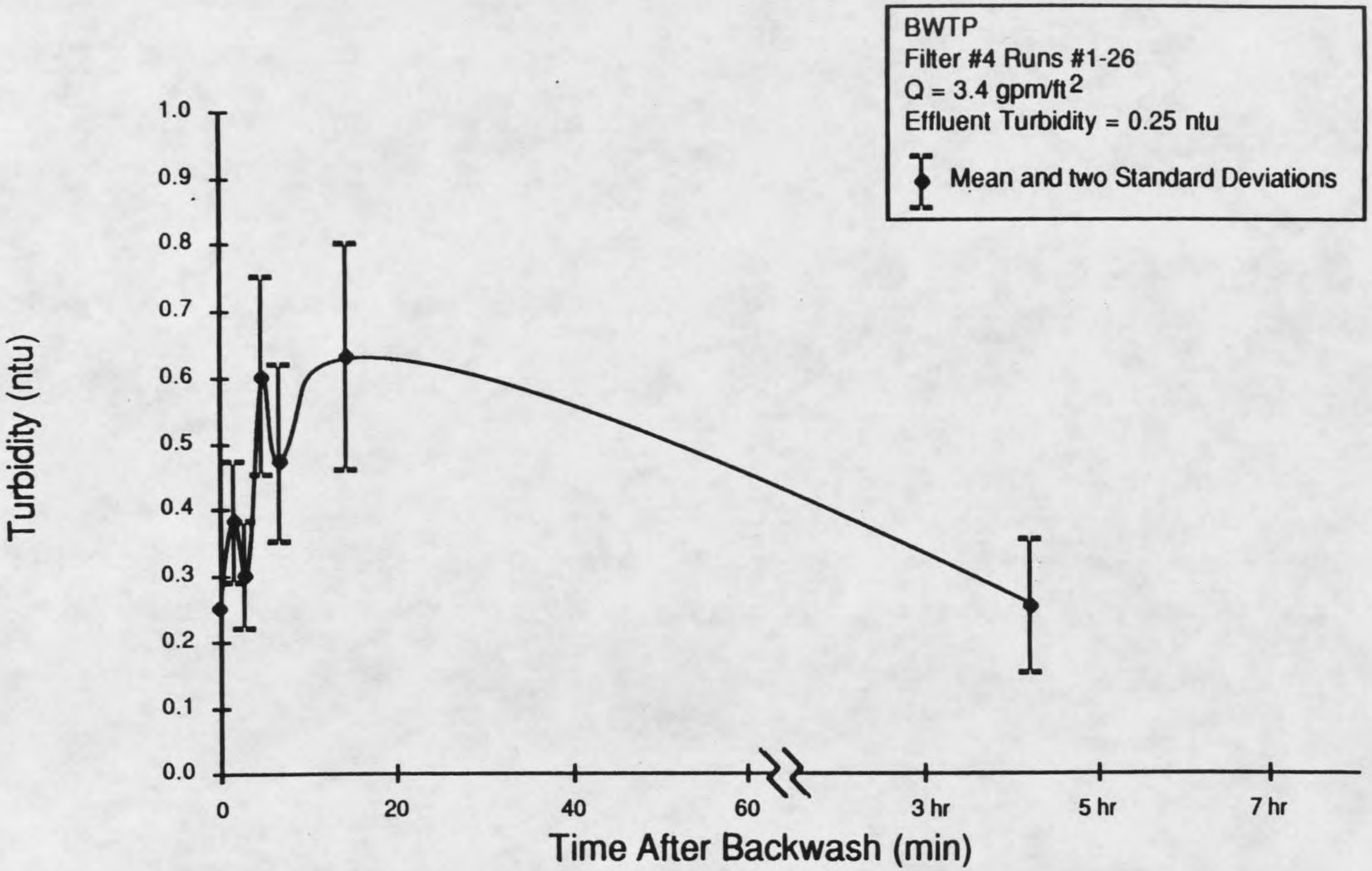

Figure 18. Mean Profile With Three Turbidity Peaks.
Filter Runs No. 1 to 26 on Filter No.4.

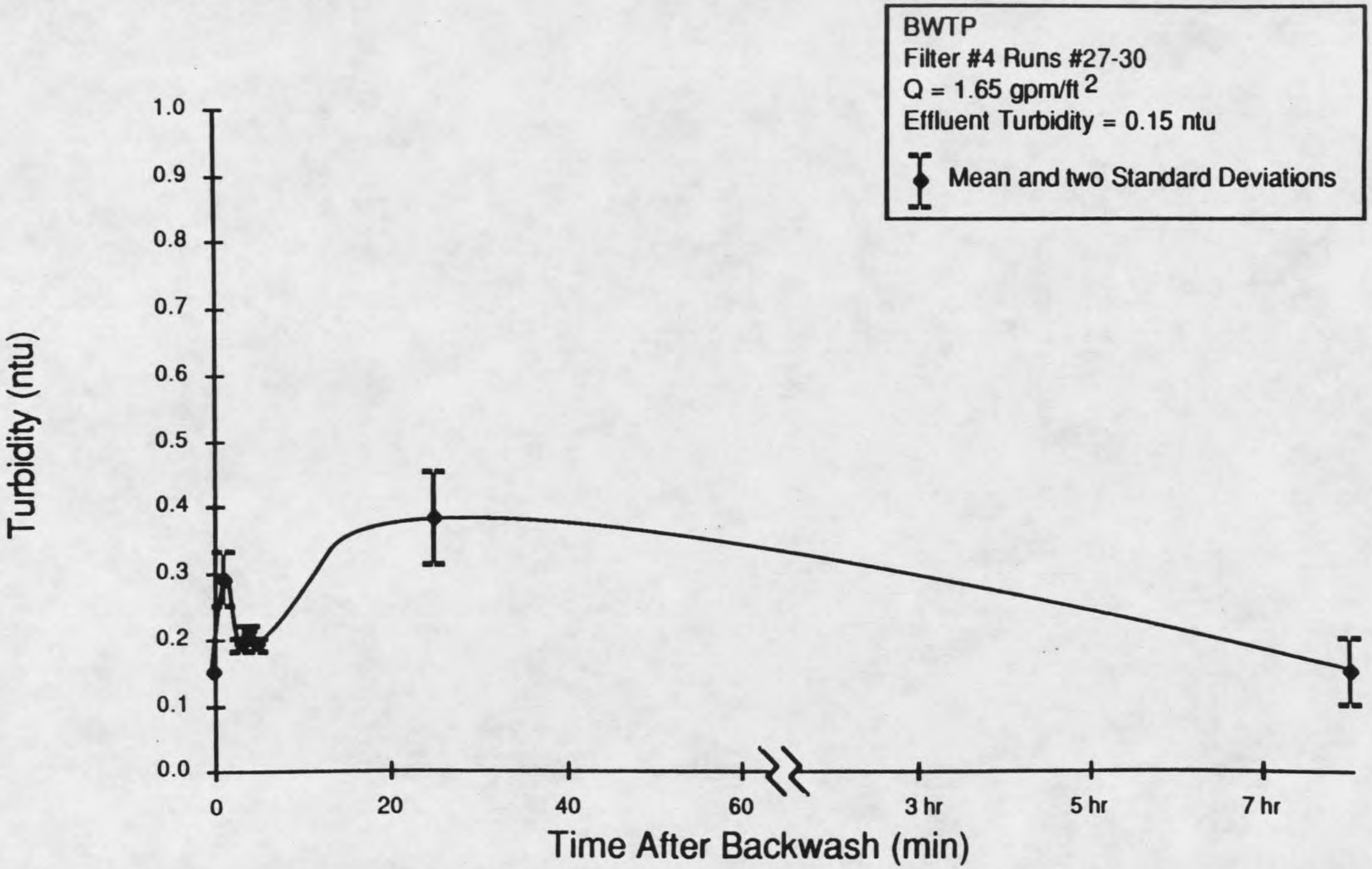

Figure 19. Mean Profile With Three Turbidity Peaks.
Filter Runs No. 27 to 30 on Filter No.4.

Table 13. Mean and Standard Deviation of Peak Turbidities By Season.

Run No.	Filter Nos.	Flow Rate (gpm/sq ft)	Peak 1 Time (min)	Peak 1 Max. Turb. (ntu)	Peak 1 Duration (min)	Peak 2 Time (min)	Peak 2 Max. Turb. (ntu)	Peak 2 Duration (min)	Peak 3 Time (min)	Peak 3 Max. Turb. (ntu)	Peak 3 Duration (hr)
Spring											
1-3 & 1-8	2-4										
Mean		= 3.0	1.81	0.38	3.5	4.6	0.62	1.9	14.5	0.67	4.6
Standard Deviation		= 0.76	1.03	0.10	0.52	0.74	0.11	0.97	5.7	0.12	3.0
Summer											
9-14	4										
Mean		= 4.1	1.5	0.43	3.8	5.7	0.70	2.6	11.3	0.76	2.6
Standard Deviation		= 0.62	0.45	0.09	0.42	0.75	0.21	1.1	3.7	0.21	2.7
Autumn											
15-21	4										
Mean		= 3.1	1.64	0.33	3.8	4.7	0.50	3.2	19.9	0.55	5.9
Standard Deviation		= 0.14	0.38	0.04	0.27	0.27	0.11	0.86	3.8	0.09	1.5
Winter											
22-30	4										
Mean		= 2.5	1.44	0.33	3.7	4.6	0.39	2.7	19.1	0.44	6.0
Standard Deviation		= 0.87	0.30	0.06	0.26	0.58	0.20	1.3	7.7	0.12	2.6

winter time. Overall, turbidities on all peaks are lowest for the filter runs with the lowest flowrates, and higher with higher flowrates.

A trend can be seen, in that even with comparable flowrates, the spring and autumn average peak turbidities differ. All peaks are higher during the spring than during the fall.

During the spring and summer, the first turbidity peak averages 0.38 to 0.43 ntu. As the year progresses, the fall and winter characteristic first peak averages 0.33 ntu in magnitude. It takes place at 1 to 2 minutes into the filter run.

The second turbidity "spike" is significant in the spring and summer; 0.62 to 0.70 ntu. By fall it has decreased in magnitude, and occurs at 4 to 5 minutes. The turbidities average 0.50 ntu in the fall, and 0.39 in the winter. The maximum turbidity recorded for this peak during the fall and winter seasons was 0.68 ntu. In contrast, the highest turbidity recorded for this peak over the year took place in the summer, and was 1.0 ntu.

The third turbidity peak occurs at 15 to 30 minutes, averaging 0.44 to 0.55 ntu, in fall and winter. In the summer it falls at 11 to 15 minutes, and is 0.67 to 0.76 ntu in magnitude.

The differing performance between the peak filter effluent turbidities in the spring as opposed to fall, under the same flowrates are most likely due to the different raw water turbidities. If anything, the cold water temperatures of the fall season should hinder coagulation and removal of turbidity, which would tend to produce a poorer quality effluent in the fall. Instead, the fall peak turbidities are lower.

Another fact which supports this idea is that the faster flowrates are associated with a quicker recovery by the filter from the high post backwash turbidities. There is a direct relationship between the length of the filter ripening period, and the flowrate. For example, in Table 11, the flow rates on filter runs #12, 13 and 14 are some of the highest recorded during this study. The length of the third turbidity peak for these three filter runs is substantially below the annual average of 4.9 hours for this plant, at 1.5, 1.3, and 0.7 hours, respectively.

O'Melia and Ali's (1978) theory of dendrite particle collection during filter ripening springs to mind. Their theory would tend to explain the more rapid recovery of filters with higher flowrates. In addition, this theory explains the quicker recovery of the filter at the Bozeman Water Treatment plant in the spring, when turbidities are high, than in the autumn, even under the same, or similar flowrates. More particles are available to form dendrites, and thus, to speed filter recovery under conditions of; (1) higher raw water turbidities, and (2) faster filter flowrates.

Helena Water Treatment Plant

Data was collected on forty-three filter runs at the HWTP (Table 14). Filter runs were divided into two groups, dependent on the mode of initiating the filter flow start up. The standard operating procedure at the HWTP is to slowly put the filter back on line, in incremental

Table 14. Summary of Filter Runs at Helena Water Treatment Plant.

Run No.	Filter No.	Date of Run	Plant Influent Temp. °C	Plant Influent pH	Plant Influent Turb. ntu	Plant Effluent Temp. °C	Plant Effluent pH	Plant Effluent Turb. ntu	Chemical Additions (mg/L) Alum	PAC[a]	PEC[b]	PEN[c]	$KMnO_4$	Cl Resid. (mg/L) INF	Cl Resid. (mg/L) EFF	Flow Rate (gpm/ sq ft)	Det. Time to Influent, T_d, (min)
1	7	5-15-86	10	8.2	3.2	9	7.4	0.15	9.3	2.9	0.89	.015	0.0	0.10	1.0	1.4	16.0
2	7	5-20-86	10	8.5	2.9	9	7.8	0.21	8.0	1.4	0.89	.015	0.0	0.10	1.1	2.0	11.2
3	7	5-24-86	11	8.1	3.1	10	7.6	0.17	8.1	2.3	1.00	.015	0.0	trace	1.0	2.0	11.2
4	7	5-27-86	11	8.6	2.6	11	7.9	0.17	7.6	3.1	1.00	.015	0.0	0.20	1.1	2.8	8.0
5	7	5-29-86	11	8.6	2.4	10	7.7	0.16	7.5	1.6	1.00	.015	0.0	0.10	1.1	1.9	11.8
6	7	6-04-86	12	8.1	2.4	11	7.5	0.13	11.0	3.7	1.00	.015	0.0	0.10	1.0	2.8	8.0
7	7	6-06-86	12	8.0	3.6	12	7.5	0.13	8.5	1.7	1.00	.015	0.0	0.05	1.0	1.9	11.8
8	7	6-09-86	12	7.9	3.2	11	7.2	0.12	12.5	0.0	1.09	.015	0.0	0.20	1.1	2.8	8.0
9	7	6-11-86	12	7.8	2.7	12	7.1	0.14	9.9	3.3	1.03	.015	0.0	0.10	1.0	2.6	8.6
10	7	6-12-86	12	7.7	4.5	12	7.1	0.15	10.2	2.4	1.04	.015	0.0	0.15	1.0	2.2	10.2
11	7	6-17-86	13	8.2	5.3	14	7.7	0.17	8.9	0.8	0.94	.015	0.0	0.10	1.1	2.3	9.8
12	7	6-18-86	13	8.3	5.7	12	7.6	0.18	9.9	2.5	0.98	.015	0.0	0.10	1.1	2.8	8.0
13	7	7-18-86	14	8.3	5.0	13	7.7	0.15	13.0	1.9	0.72	.015	0.0	0.20	1.2	2.6	8.6
14*	7	7-18-86	14	8.5	4.0	13	7.8	0.21	13.0	1.9	0.72	.015	0.0	0.15	1.3	3.8	5.9
15*	7	7-18-86	14	8.3	5.0	13	7.9	0.23	13.0	1.9	0.72	.015	0.0	0.15	1.3	1.3	17.3
16	7	8-05-86	14	7.8	2.5	13	7.4	0.15	13.0	2.4	0.57	.022	0.0	0.15	1.2	2.6	8.6
17	7	8-21-86	15	7.5	4.0	14	7.1	0.11	13.4	6.6	0.70	.022	0.0	0.04	1.2	2.6	8.6
18	7	8-23-86	15	7.5	3.4	14	7.6	0.14	11.6	11.0	0.82	.022	0.0	0.05	1.6	2.6	8.6
19	7	8-25-86	15	7.6	3.2	14	7.4	0.13	11.1	9.1	0.72	.022	0.0	0.05	1.2	2.6	8.6
20	7	8-26-86	15	7.5	3.3	15	7.7	0.15	11.3	8.3	0.69	.022	0.0	0.05	1.2	2.6	8.6
21	7	8-28-86	16	7.4	2.2	15	7.2	0.12	10.6	8.1	0.67	.022	0.0	0.04	1.4	2.0	11.2
22	7	8-29-86	16	7.4	1.9	15	7.3	0.16	11.5	9.4	0.71	.022	0.0	0.02	1.1	2.6	8.6
23	7	8-29-86	16	7.4	2.1	15	7.3	0.17	11.5	9.4	0.71	.022	0.0	0.05	1.2	2.6	8.6
24	7	8-30-86	16	7.5	2.9	16	7.2	0.13	12.2	6.5	0.80	.022	0.0	0.05	1.3	1.9	11.8

Table 14. (Continued.)

Run No.	Filter No.	Date of Run	Plant Influent Temp. °C	Plant Influent pH	Plant Influent Turb. ntu	Plant Effluent Temp. °C	Plant Effluent pH	Plant Effluent Turb. ntu	Chemical Additions (mg/L) Alum	PAC[a]	PEC[b]	PEN[c]	$KMnO_4$	Cl Resid. (mg/L) INF	Cl Resid. (mg/L) EFF	Flow Rate (gpm/sq ft)	Det. Time to Influent, T_d, (min)
26	7	9-05-86	17	7.8	2.6	16	7.4	0.18	11.3	7.6	0.94	.022	0.0	0.04	1.2	2.8	8.0
27	7	9-08-86	16	7.7	2.3	16	7.2	0.11	27.7	28.0	0.65	.022	1.50	0.03	1.3	1.9	11.8
28	7	9-10-86	16	7.6	4.0	15	7.4	0.20	15.9	50.9	0.68	.022	2.00	0.04	1.5	2.6	8.6
29	7	9-13-86	16	8.0	3.4	15	7.2	0.12	15.2	55.0	0.70	.022	2.00	trace	1.3	2.3	9.8
30	7	9-17-86	15	7.9	3.4	14	7.3	0.18	12.0	61.0	0.66	.022	2.25	trace	1.3	2.3	9.8
31	7	9-21-86	16	8.1	3.6	14	7.4	0.17	12.9	67.0	0.69	.022	2.25	trace	1.3	2.3	9.8
32	7	9-23-86	15	8.2	3.4	13	7.4	0.16	9.5	78.5	0.67	.022	2.25	trace	1.3	2.1	10.7
33	7	10-14-86	15	8.3	3.8	11	7.2	0.17	31.9	98.0	0.66	.022	2.75	trace	1.1	2.6	8.6
34	7	10-17-86	13	8.4	3.7	11	7.2	0.12	31.4	108.3	0.63	.022	2.75	trace	0.9	2.6	8.6
35	7	10-28-86	13	8.7	3.7	10	7.3	0.17	32.4	9.6	0.65	.022	1.00	trace	1.1	2.6	8.6
36	7	12-19-86	6	8.5	1.6	4	7.5	0.17	12.5	7.2	0.62	.022	0.0	0.18	1.1	2.6	8.6
37	7	12-30-86	6	8.4	1.6	4	7.3	0.18	14.2	8.9	0.63	.022	0.0	0.09	1.1	2.6	8.6
38	7	1-09-87	6	8.2	1.9	4	7.2	0.13	14.6	6.3	0.62	.022	0.0	0.05	1.1	2.6	8.6
39	7	1-19-87	6	8.4	1.8	4	7.3	0.17	15.1	3.5	0.66	.022	0.0	0.05	1.1	2.6	8.6
40	7	1-23-87	5	8.5	1.7	4	7.4	0.14	16.5	9.1	0.67	.022	0.0	0.05	1.1	2.6	8.6
41	7	1-29-87	5	8.4	1.9	4	7.4	0.17	13.2	7.6	0.67	.022	0.0	0.17	1.0	2.6	8.6
42	7	2-04-87	5	8.2	1.8	5	7.2	0.15	14.7	3.4	0.65	.022	0.0	0.10	1.0	2.6	8.6
43	7	2-09-87	6	8.3	1.7	5	7.2	0.12	13.6	5.2	0.59	.022	0.0	0.04	1.0	2.6	8.6
Mean		-	12	8.0	3.0	11	7.4	0.15	13.6	17.6	0.78	.020	0.46	0.09	1.2	2.4	9.5
Maximum		-	17	8.7	5.7	16	7.9	0.21	32.4	108.3	1.09	.022	2.75	0.20	1.6	2.8	16.0
Minimum		-	5	7.4	1.6	4	7.1	0.10	7.5	0.0	0.57	.015	0.00	0.02	0.9	1.4	8.0
Standard Deviation		-	3.8	0.39	1.0	4	0.2	0.03	-	-	-	-	-	0.05	0.15	0.34	1.6

[a]PAC - Powdered Activated Carbon; [b]PEC - Cationic Polymer (Nalco 8105); [c]PEN - Non-ionic POlymer (Nalco 8170)

[*]Run Nos. 14 and 15 are not included in mean and standard deviation calculations.

flow rate steps (Table 15). Other filter runs were begun in a "non-incremental" mode, in order to compare the filter runs with the BWTP (Table 16). Figure 20 shows the contrast in turbidity profiles between a filter started incrementally and non-incrementally after a backwash.

Two filter runs, #14 and 15, were averaged separately, both in the master table for the HWTP, (Table 13), and in Table 15, the non-incremental start up group of filter runs. This was done because these filter runs were conducted at filter flowrates higher and lower than any other runs conducted. Both of these runs should be considered unrepresentative of the operating filters at the HWTP. Filter runs #13, 14 and 15 were made on the same day, 7-18-86. The first backwash and filter run, #13 was made at 2.6 gpm/ft^2. The filter run was 4.0 hours. At this time the filter was backwashed again. The next filter run, #14, was conducted at 3.8 gpm/ft^2, and lasted only 75 minutes. The peak turbidity reached was 2.0 ntu. This is probably a reasonable peak turbidity for this flowrate, much higher than is normally utilized at this plant. The third filter run for the day, run #15, was conducted at 1.3 gpm/ft^2. The peak filter effluent turbidity was 7.4 ntu, quite a bit higher than the average peak turbidity of 0.28 ntu at 2.5 gpm/ft^2! This filter run lasted only 50 minutes.

The HWTP characteristic turbidity profile for non-incremental post backwash start up remained much the same for the duration of the year. This is due to the fairly constant flowrates maintained at this water treatment facility. From Figure 21, below, it is obvious that this

Table 15. Turbidity Peaks at Helena Water Treatment Plant Incremental Start Up.

Run No.	Date of Run	Flow Rate (gpm/sq ft)	Peak 1 Time (min)	Peak 1 Turb. (ntu)	Peak 1 Duration (min)	Peak 2 Time (min)	Peak 2 Turb. (ntu)	Peak 2 Duration (hr)	Det. Time to Influent, T_d, (min)
13	7-18-86	2.6	2.5	0.20	8.0	9.0	0.42	4.0	8.6
14*	7-18-86	3.8	8.0	0.40	12.0	20.0	2.00	1.3	5.9
15*	7-18-86	1.3	1.0	0.26	4.0	18.5	7.40	0.8	17.3
16	8-05-86	2.6	4.0	0.25	5.0	8.0	0.29	4.0	8.6
23	8-29-86	2.6	5.0	0.25	6.0	13.0	0.28	3.0	8.6
24	8-30-86	1.9	6.0	0.18	11.0	25.0	0.18	4.0	11.8
25	9-03-86	1.9	7.0	0.15	10.0	20.0	0.19	4.0	11.8
26	9-05-86	2.8	5.0	0.28	8.0	20.0	0.33	0.8	8.0
27	9-08-86	1.9	5.0	0.27	8.0	20.0	0.31	3.0	11.8
28	9-10-86	2.6	6.0	0.24	8.0	15.0	0.28	3.0	8.6
29	9-13-86	2.3	5.0	0.36	6.0	10.0	0.32	4.0	9.8
30	9-17-86	2.3	5.0	0.27	8.0	12.0	0.28	0.8	9.8
31	9-21-86	2.3	5.0	0.29	6.0	12.0	0.38	4.0	9.8
32	9-23-86	2.1	5.0	0.22	7.0	17.0	0.39	4.0	10.7
33	10-14-86	2.6	7.0	0.23	9.0	12.0	0.23	2.0	8.6
34	10-17-86	2.6	7.0	0.19	9.0	16.0	0.19	2.0	8.6
35	10-28-86	2.6	3.0	0.26	5.0	17.0	0.31	2.0	8.6
36	12-19-86	2.6	2.5	0.18	7.0	11.3	0.28	4.0	8.6
37	12-30-86	2.6	1.5	0.16	6.5	18.0	0.21	0.8	8.6
38	1-09-87	2.6	3.0	0.21	4.5	10.0	0.28	4.0	8.6
39	1-19-87	2.6	4.0	0.23	5.0	12.0	0.25	4.0	8.6
40	1-23-87	2.6	1.0	0.23	3.0	6.0	0.22	4.0	8.6
41	1-29-87	2.6	2.0	0.25	5.0	10.0	0.31	2.0	8.6
42	2-04-87	2.6	1.0	0.22	4.0	6.0	0.30	4.0	8.6
43	2-09-87	2.6	6.0	0.26	9.0	16.0	0.23	4.0	8.6
Mean	-	2.5	4.3	0.23	6.9	13.7	0.28	3.1	9.2
Maximum	-	2.8	7.0	0.36	11.0	25.0	0.42	4.0	11.8
Minimum	-	1.9	1.0	0.15	3.0	6.0	0.18	0.8	8.0
Standard Deviation	-	0.3	1.9	0.05	2.0	4.9	0.06	1.2	1.2

*Run Nos. 14 and 15 are not included in mean and standard deviation calculations.

Table 16. Turbidity Peaks at Helena Water Treatment Plant Non-Incremental Start Up.

Run No.	Date of Run	Flow Rate Reached (gpm/sq ft)	Duration of Incremental Startup (min)	Turbidity Peak Time (min)	Turbidity Peak Turb. (ntu)	Turbidity Peak Duration (hr)	Det. Time to Influent, T_d, (min)
1	5-15-86	1.4	11	15	0.30	0.5	16.0
2	5-20-86	2.0	30	25	0.39	0.5	11.2
3	5-24-86	2.0	60	25	0.31	1.0	11.2
4	5-27-86	2.8	12	30	0.29	1.0	8.0
5	5-29-86	1.9	12	25	0.33	1.0	11.8
6	6-04-86	2.8	11	19	0.27	1.0	8.0
7	6-06-86	1.9	12	5	0.27	1.0	11.8
8	6-09-86	2.8	13	16	0.17	1.0	8.0
9	6-11-86	2.6	16	0	0.31	1.0	8.6
10	6-12-86	2.2	60	24	0.29	1.0	10.2
11	6-17-86	2.3	10	17	0.29	1.0	9.8
12	6-18-86	2.8	11	15	0.26	0.8	8.0
17	8-21-86	2.6	19	5	0.29	1.0	8.6
18	8-23-86	2.6	25	16	0.22	1.0	8.6
19	8-25-86	2.6	16	17	0.21	1.0	8.6
20	8-26-86	2.6	19	19	0.18	1.0	8.6
21	8-28-86	2.0	3	17	0.38	1.0	11.2
22	8-29-86	2.6	16	16	0.43	1.0	8.6
Mean	=	2.4	20	17	0.29	0.9	9.8
Maximum	=	2.8	60	30	0.43	1.0	16.0
Minimum	=	1.4	3	0	0.18	0.5	8.0
Standard Deviation	=	0.4	16	8	0.06	10.0	2.1

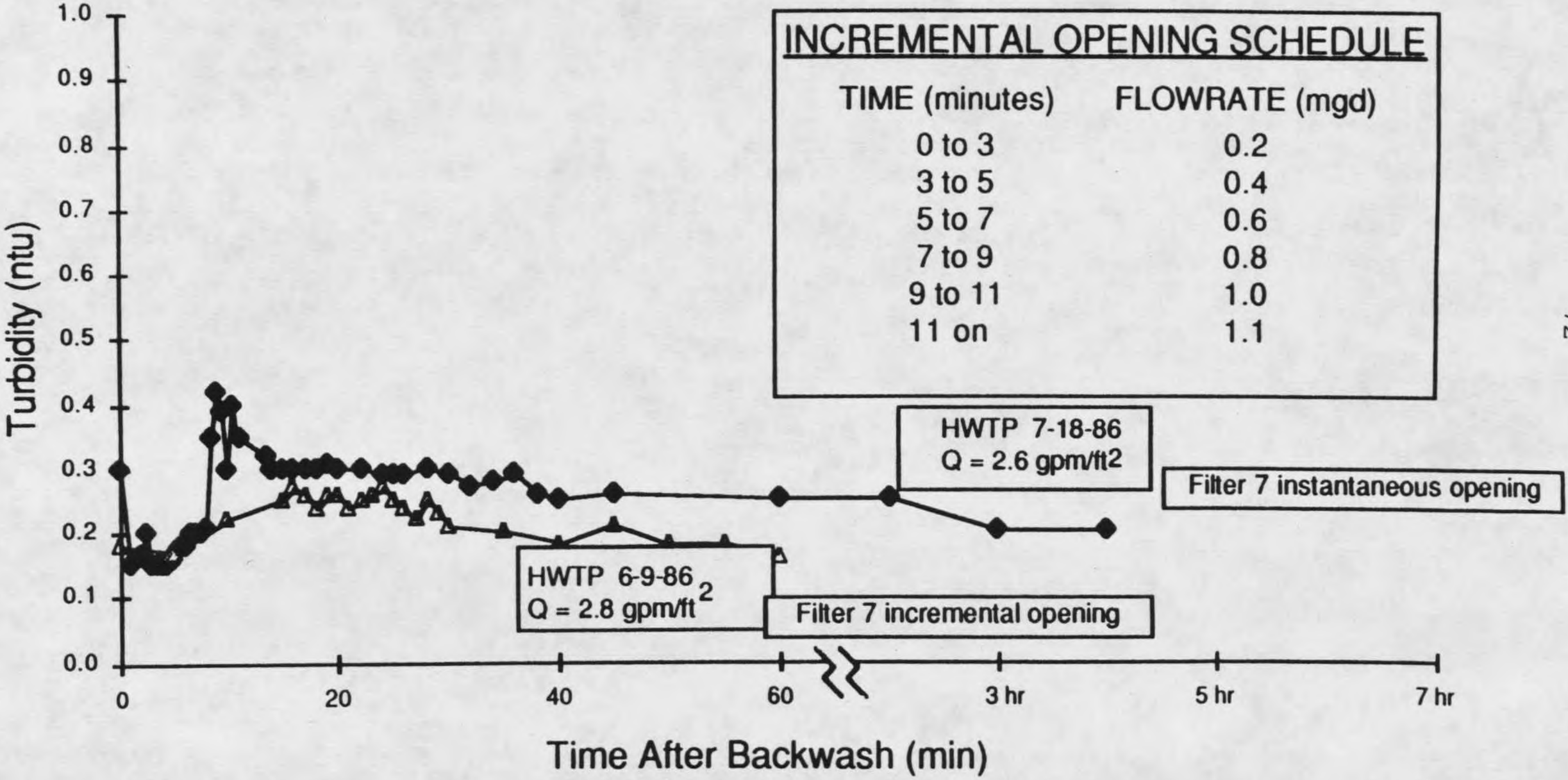

Figure 20. Contrast in Turbidity Profiles Between Incremental vs. Instantaneous Start Up of Filtration. Helena Water Treatment Plant.

plant has a much different turbidity profile that the BWTP for the post backwash period.

The first peak in turbidity generally occurs at 3 to 5 minutes. This turbidity increase (it can hardly be called a peak), averages 0.23 ntu. The second, larger turbidity peak resembles the BWTP's third turbidity peak, and averages 0.28 ntu's, occurring about 14 minutes following backwash. It is also notable that the calculated detention times for the non-incremental startup at the HWTP are not as accurate an estimate of the time at which the peak turbidity will occur, as they are for the BWTP. Some of the detention times are very close to the time at which the peak turbidity occurs, but some are quite different. Since the HWTP does not exhibit peak turbidities as striking as does the BWTP, this non-correspondence with detention times is not unexplained. Also, the nature of grab samples, in terms of a small volume sample being collected to represent a large volume, at one instant, may cause the accuracy not to be as high as for a continuous sample.

From these turbidities, it can be surmised that, even with an abrupt startup, the HWTP turbidities remain low during the post backwash period. Leonard Willett, supervisor at the HWTP, has mentioned that the non-ionic polymer is added to the raw water as a filter aid, specifically to maintain low post-backwash turbidities. The polymer was in use during all of the filter runs observed for this study, so the relationship between non-ionic polymer and post backwash turbidity magnitudes was not tested here.

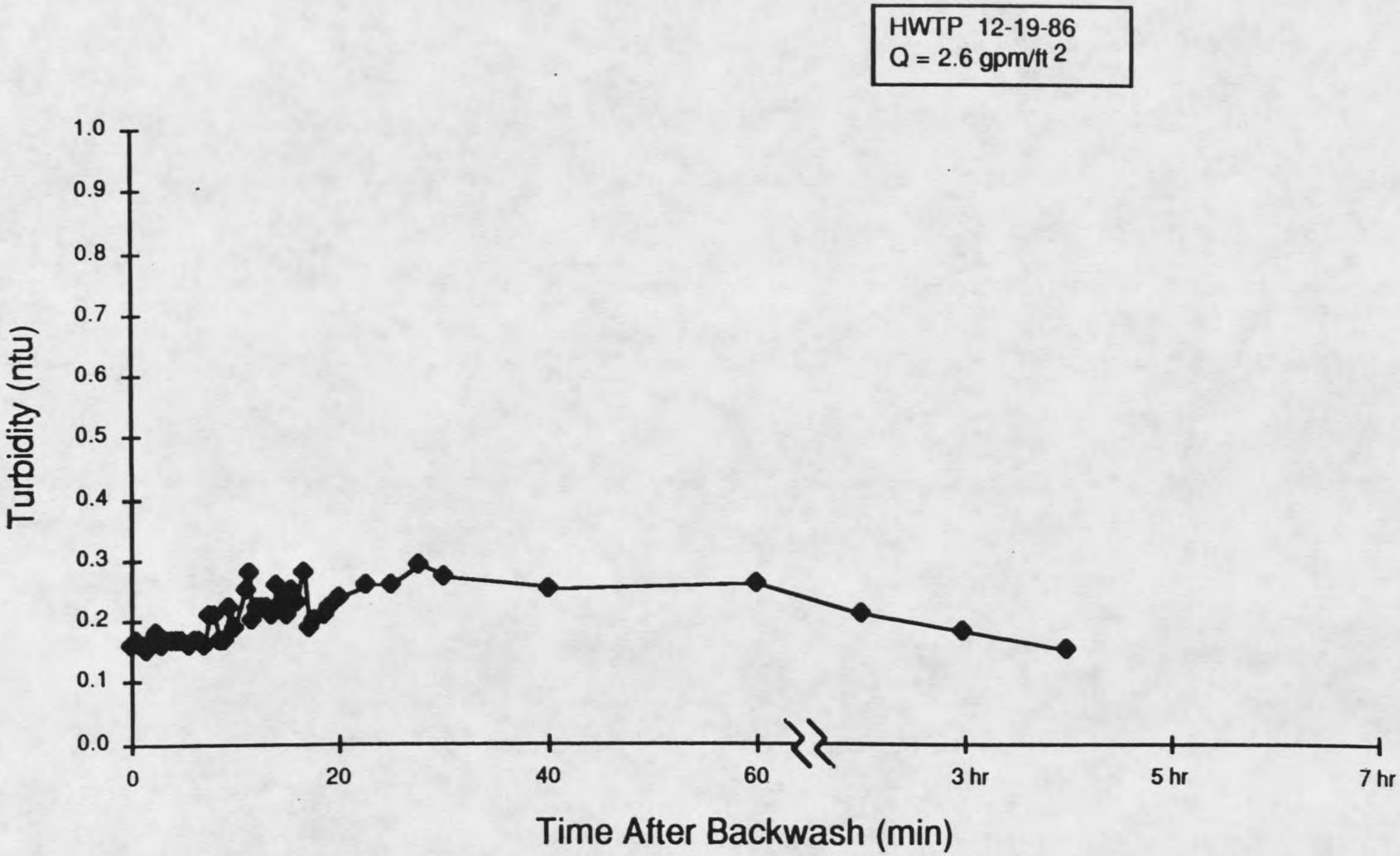

Figure 21. Characteristic Turbidity Profile for Helena Water Treatment Plant.

A theoretical, or composite post backwash turbidity profile was produced from the data in Table 12 (Figure 22). The mean recovery time for the filters at the HWTP was 3.1 hours to reach a filter effluent turbidity of 0.15 ntu.

It is hard to compare the BWTP and HWTP post backwash turbidity profiles, due to the myriad of variables involved. It is obvious, however, that the HWTP maintains lower turbidities during the post backwash portion of the filter run. All of the basic causes for these lower turbidities cannot be proven conclusively. However, two factors which do contribute to the lower turbidities are; (1) lower raw water turbidities, and (2) lower filter flow rates.

The ideal raw water turbidities for minimizing post backwash turbidities are stable, and fairly low. The mean raw water turbidities for the BWTP and the HWTP are 2.8 and 3.0 ntu, respectively. But the standard deviations about those means are 2.6 and 1.0, respectively. A more constant influent turbidity probably helps to maintain low filter effluent turbidities. Even though more particles in the filter influent may help form dendrites, and speed the filter ripening, turbidity spikes probably do not enhance this effect.

The effect of flowrate upon the filter is best illustrated by the difference, at the BWTP, in the post backwash turbidity profile between the profile at 4.5 gpm/ft^2 and the mid-winter profile at flowrates of 1.7 gpm/ft^2. The BWTP turbidity profile during the low filter flowrates is strikingly similar to that of the HWTP, whereas, during the balance of the year it is entirely dissimilar (Figure 23). In addition, the raw

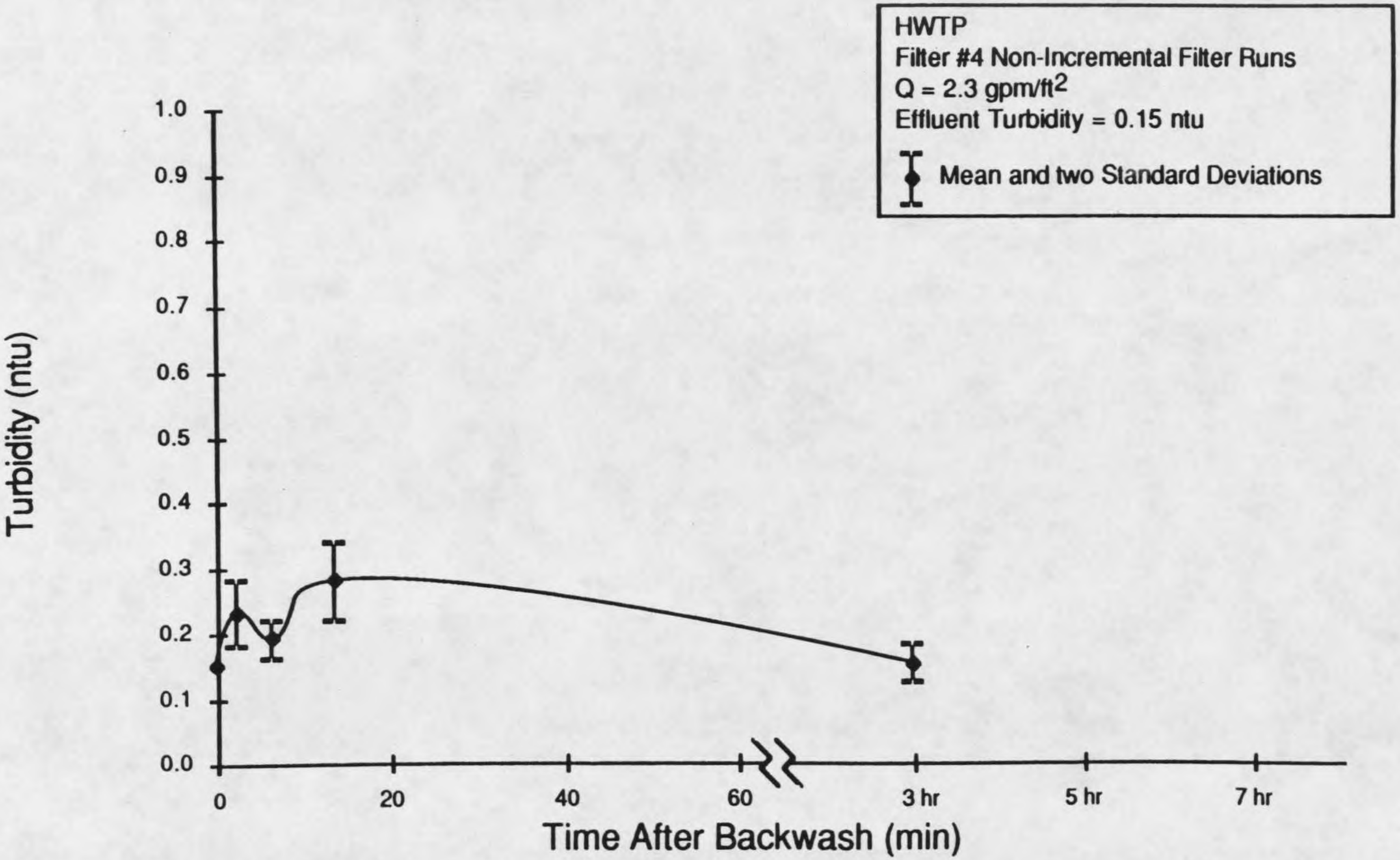

Figure 22. Mean Profile With Two Turbidity Peaks.
Filter Runs No. 13 to 43.

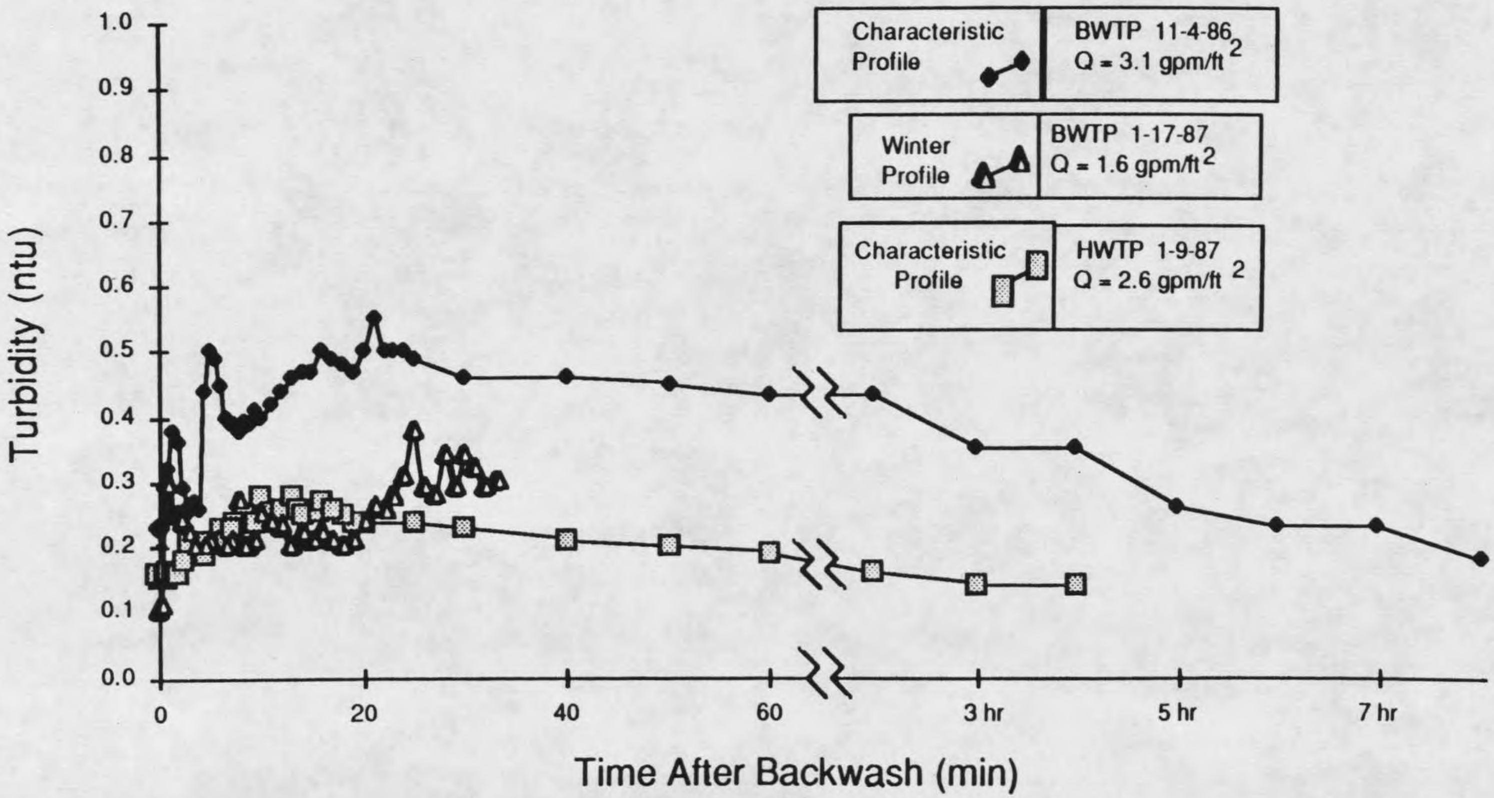

Figure 23. Similarities Between Bozeman and Helena Turbidity Profiles During Low Filtration Rates.

water turbidities drop dramatically from summer to winter at the BWTP. In the winter, the raw water turbidity generally stays below 1.0 ntu. The HWTP raw water turbidities are constant, year round, near 2 ntu.

Tracer Studies

Tracer studies were conducted at the BWTP in order to determine: (1) the origin of the turbidity peaks, and (2) why the BWTP exhibited three turbidity peaks, while the HWTP showed a dual peak characteristic.

After considering various strategies, a fluoride tracer was decided upon. The major problem was that in a municipal water treatment facility, dye cannot be added as a tracer, as would be done in a pilot plant scale study. The fluoride tracer is perhaps not as accurate as a dye tracer, due to: (1) background fluoride levels must be accounted for, and (2) fluoride, in the powdered Na_2SiF_6 form is cumbersome to use.

During the course of this study, background fluoride levels were between 0.20 and 0.01 mg/L. The background levels were variable within the course of a filter run. This variability was offset during the fluoride tracer studies by using as high a concentration of fluoride as possible in the tracer, and by using a pump which could inject the fluoride into the influent at a high enough rate.

The powdered fluoride form used for the tracer solution was cumbersome. This is mainly due to the ionic composition (59.5% F^-) and grade (98% purity). Also, temperatures within the water treatment facility near the filters was between 2 and 10 degrees centigrade, depending on the season. The solubility of the Na_2SiF_6 is dependent on temperature, and it did not dissolve well at the temperatures under which we were operating. Thus, the volume required for the tracer was enormous, and the tracer was generally stopped after 30 to 90 minutes into the filter run, because of the logistics of how much tracer solution could be handled. However, these problems were overcome (after a few trials and errors!), and several good fluoride tracer studies were completed. Four tracer studies were conducted, three of which provided information about the operation of the filter. The first fluoride did not provide any information, due to troubles in achieving and maintaining a high tracer concentration in the influent.

Figure 24 illustrates the fluoride tracer runs. The three turbidity peaks can be seen. The tracer solution was added to the influent, immediately upon the influent valve to the filter opening after backwash. Fluoride concentrations in the filter effluent are expressed as a percent of total.

The tracer marks the influent, as opposed to the backwash water remnants. It can be seen that the third turbidity peak is due to the filter influent. The estimated plug flow detention time of the backwash water remnants for this particular flowrate is 13.9 minutes. The appearance of the fluoride complements this calculation nicely. Also, the first and second turbidity peaks are clearly shown to be associated with the backwash water remnants.

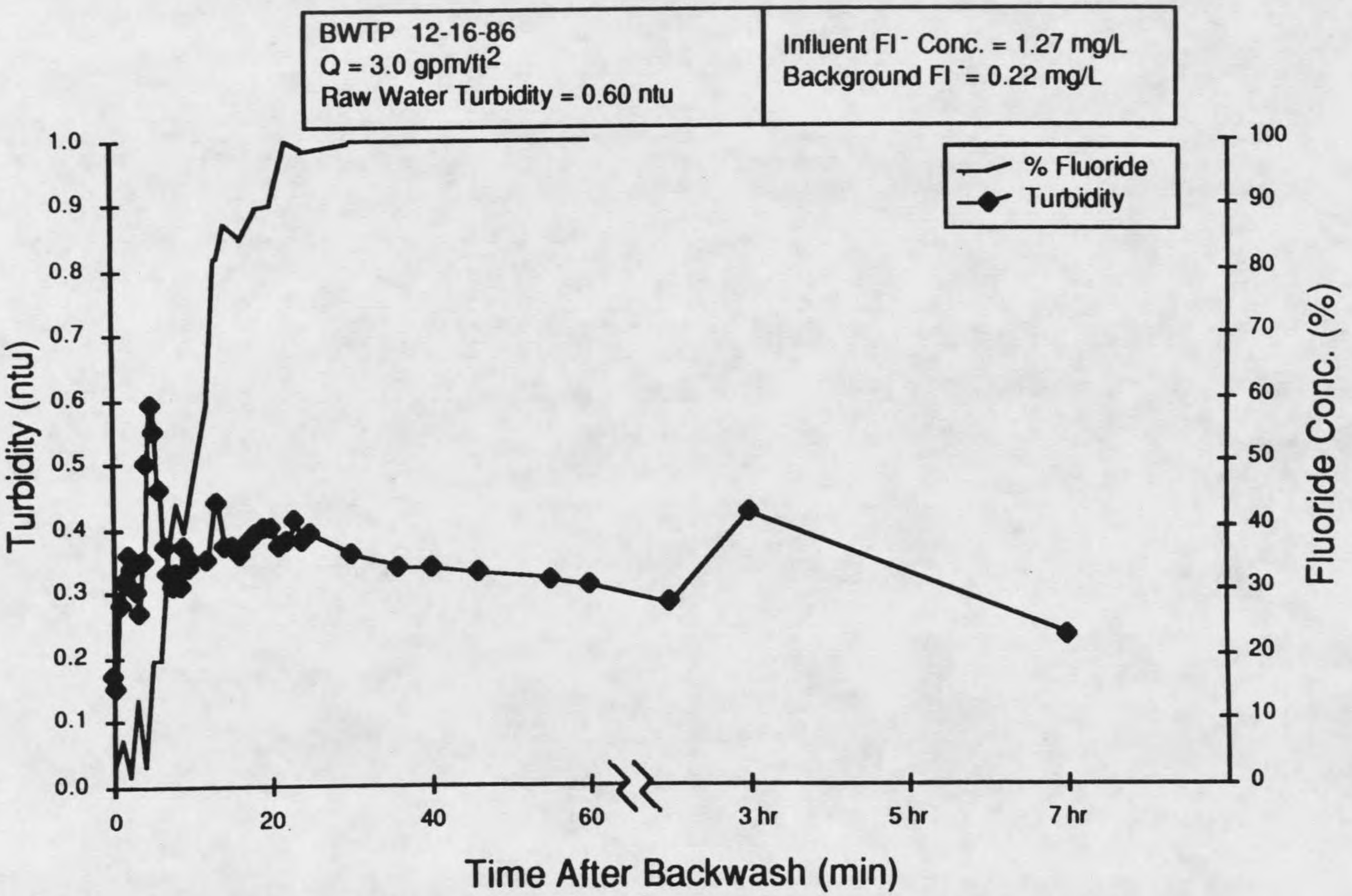

Figure 24. Fluoride Tracer Compared With Turbidity Profile.
Bozeman Water Treatment Plant.
Filter detention time = 13.9 min.

Hoping to isolate one of the two remaining turbidity peaks, a "reverse" tracer was utilized. The BWTP does not prechlorinate the filter influent. Thus, after a backwash, the filter effluent should show a chlorine residual as the backwash water remnants are filtered. Four filter runs were analyzed for the presence of chlorine in the filter effluent after a backwash. Figure 25 illustrates one of these.

The backwash water remnants are definitely associated with the first turbidity peak. The graph also shows the influent mixing and dispersion which occurs as the influent water meets the backwash remnants above the media. The second spike shaped turbidity peak is not associated with the backwash water remnants, except in terms of mixing. It is also worthwhile to note that the calculated detention time for this filter run was 10.7 minutes, almost exactly what is seen in Figure 25.

The question then remained, what is the source of the second turbidity "spike" at the BWTP? Also, why does it disappear at lower flow rates so that the BWTP turbidity profiles come to resemble the HWTP turbidity profiles? In all past studies only two peaks in the ripening period have been shown. One corresponds to the backwash remnants and the second at the interface between the remnant above the filter and the influent water. Therefore, the turbidity "spike" (the second peak at the BWTP) is probably system specific to the Bozeman Treatment Plant.

The second turbidity peak at the BWTP is caused by the closing of the filter-to-waste valve, and the opening of the valve which directs the effluent to the clear well. This is supported by these facts:

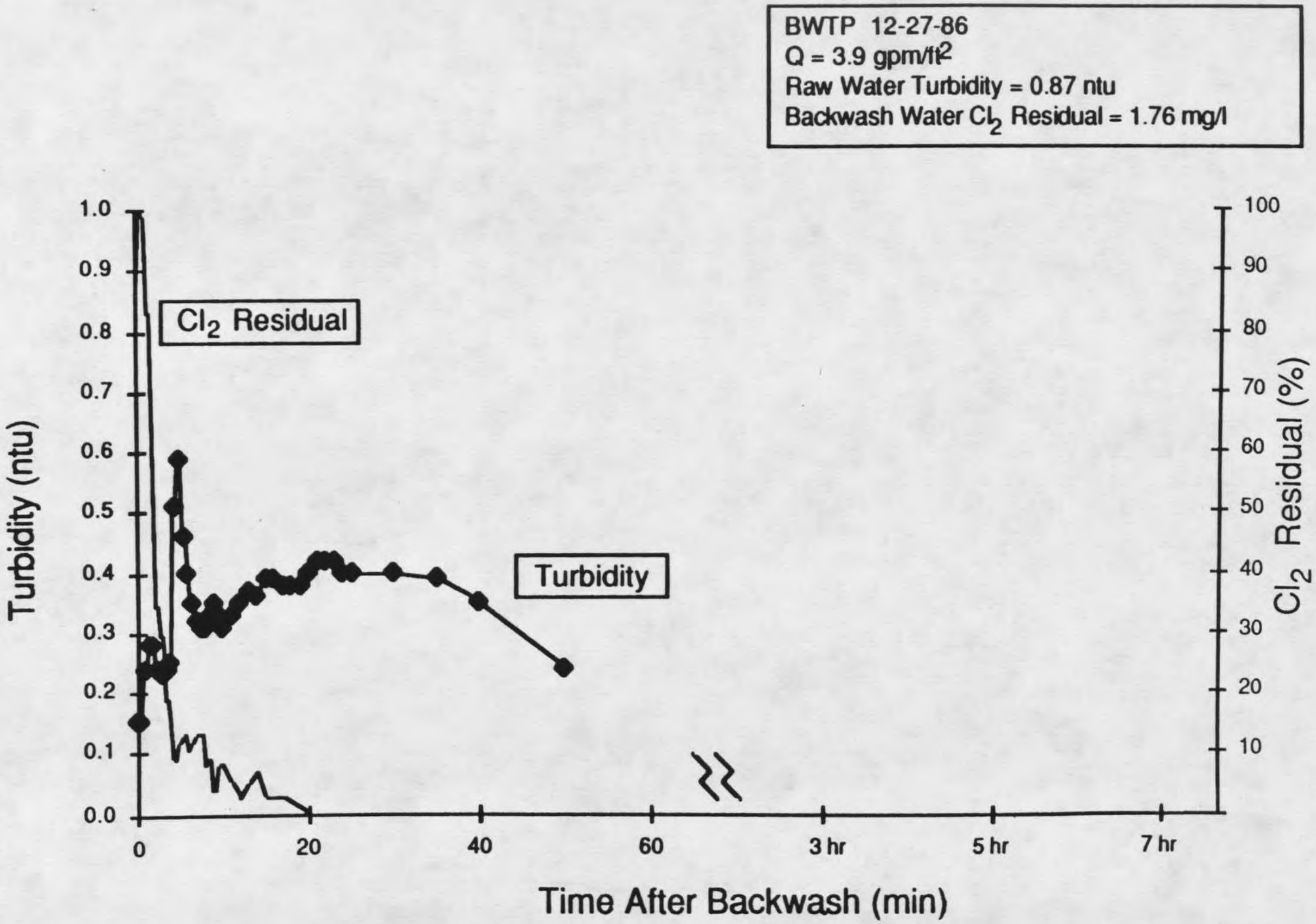

Figure 25. Residual Chlorine Tracer Compared With Turbidity Profile.
Bozeman Water Treatment Plant.
Filter detention time = 10.7 min.

1. The second turbidity peak occurs at almost exactly 4 to 5 minutes. The turbidity peak can actually be seen, if a continuous monitoring device is used to measure the effluent turbidity. The filter-to-waste valve closes at 4.0 minutes after backwash. The clear well valve opens 100% at about 4.25 minutes, then partially closes to accommodate the effluent flow. At this time the filter effluent turbidities begin to rise. The turbidities usually rise extremely quickly, so that within 30 seconds or so the peak has been reached.

2. The maximum turbidity which is reached is proportional to the flowrate at which the filter is operating. As lower flow rates are used during the winter months, the turbidity spike disappears. The sudden closing and opening of the filter-to-waste and clear well valves produce a much smaller rate change when the filter operates at a lower flow rate. It is well known that sudden, large rate changes (Cleasby, et al., 1963) can cause a filter to produce turbidity spikes in the filter effluent. Thus, both water treatment plants exhibited a dual peaked post backwash turbidity characteristic. The first turbidity peak is a function of the backwash water remnants. The second peak is largely due to the influent water, and the period and magnitude of this peak is a function of both flow rate and raw water turbidity.

The findings from this study complement Cranston's (1987) "filter ripening sequence" theory. The three steps of his theory are supported by evidence gathered herein.

I. The remnant stage. The remnant stage is associated with the backwash water remnants within the underdrains, within the media, and above the media, up to the backwash gutter. The first turbidity peak at both the BWTP and the HWTP increases in turbidity as a function of the flowrate at which the filter is put back on line (Refer to Tables 11 and 15). Cranston states that this peak of turbidity is caused either by particles sheared off the media at the beginning of the filtration cycle, or at the end of backwash as the media particles collide with each other. Although he did not observe this turbidity peak within the pilot plant data he collected, Cranston based his assertion on data gathered by this author at the BWTP and the HWTP.

The HWTP uses an incremental shut down of the backwash water flow rate, and this plant also does have lower initial turbidity peaks than the BWTP. However, the relationship between these two variables cannot be directly related based on the work of this study.

A relationship which can be substantiated, though, is that if a filter is put back on line at the full filter flow rate, the initial turbidity peak is directly related to that flow rate. As mentioned above, the filter flow rate at which a filter is started immediately following backwash is proportional to the turbidity peak. This is a good argument for the incremental start up of a filter after a backwash.

Also, at the BWTP, the spike shaped second turbidity peak is not a function of the filter itself; rather, it is a product of the closing of the filter-to-waste valve and opening of the clear well valve, and the flow rate at which the filter is operating. Since the magnitude of this peak is related to the filter flow rate, it follows that the mechanism by which the turbidities are produced are the shearing of particles from the filter media upon the opening of the clear well valve. This turbidity peak is produced by the sudden rate changes on an operating filter.

II. Influent mixing and particle stabilization stage. This stage is a function of the influent water and the third backwash remnant. As the influent water disperses into the backwash water remnant above the filter media, the influent flocs become partially stabilized, due to the non-flocculated backwash water remnants. The "weakened" (in terms of particle destabilization) flocs pass through the filter media.

The last turbidity peak evidenced at both water treatment plants is associated with this stage. The concurrence of the calculated detention times with the highest turbidity recorded for the filter run is evidence for this mechanism. The detention time gives the approximate travel time of the boundary between the influent water and the backwash water remnants above the filter through the filter unit.

Additionally, the fluoride tracer studies support this theory. The appearance of the peak turbidity occurs with the appearance of the tracer fluoride in the effluent.

III. Filter media conditioning stage. This refers to the portion of the post backwash period in which the turbidities slowly improve. In this study, O'Melia and Ali's dendrite and particle accumulation theory seems to hold. At similar flow rates, the water with the higher turbidities has a shorter recovery period from the initial degradation of the filter run. With similar influent turbidities, the filter with higher flow rates will recover more quickly. Both of these findings support the dendrite theory.

Particulate Analysis

A particulate analysis was done on raw water and on the filter effluent at the BWTP to determine the potential for Giardia cyst transmission during the initial stages of filtration. The analysis was done by Ms. Donna Howell, at the Montana Department of Health and Environmental Sciences, Water Quality Bureau.

Four separate samples were taken; raw water, and three filter effluent samples over time as the filter run progressed. The effluent samples were taken on the following schedule:

Sample #1	0 to 7.5 minutes after backwash
Sample #2	8.5 to 60 minutes after backwash
Sample #3	60 to 120 minutes after backwash

The raw water analysis revealed a large spectrum of particle sizes present. No Giardia cysts were detected. There were "...sufficient organisms the size of Giardia cysts to determine the efficiency of cyst-sized particle removal."

Sample #1 showed good removal of debris, although a moderate amount of diatoms were present. The diatoms were Giardia sized. Sample #2 was very clean. Some diatoms were present, but were rare. Sample #3 showed excellent removal of all debris. This sample was significantly cleaner than samples 1 or 2.

Figure 26 is the turbidity profile for the filter run which was analyzed for particulates. Sample #1 includes the first turbidity peak,

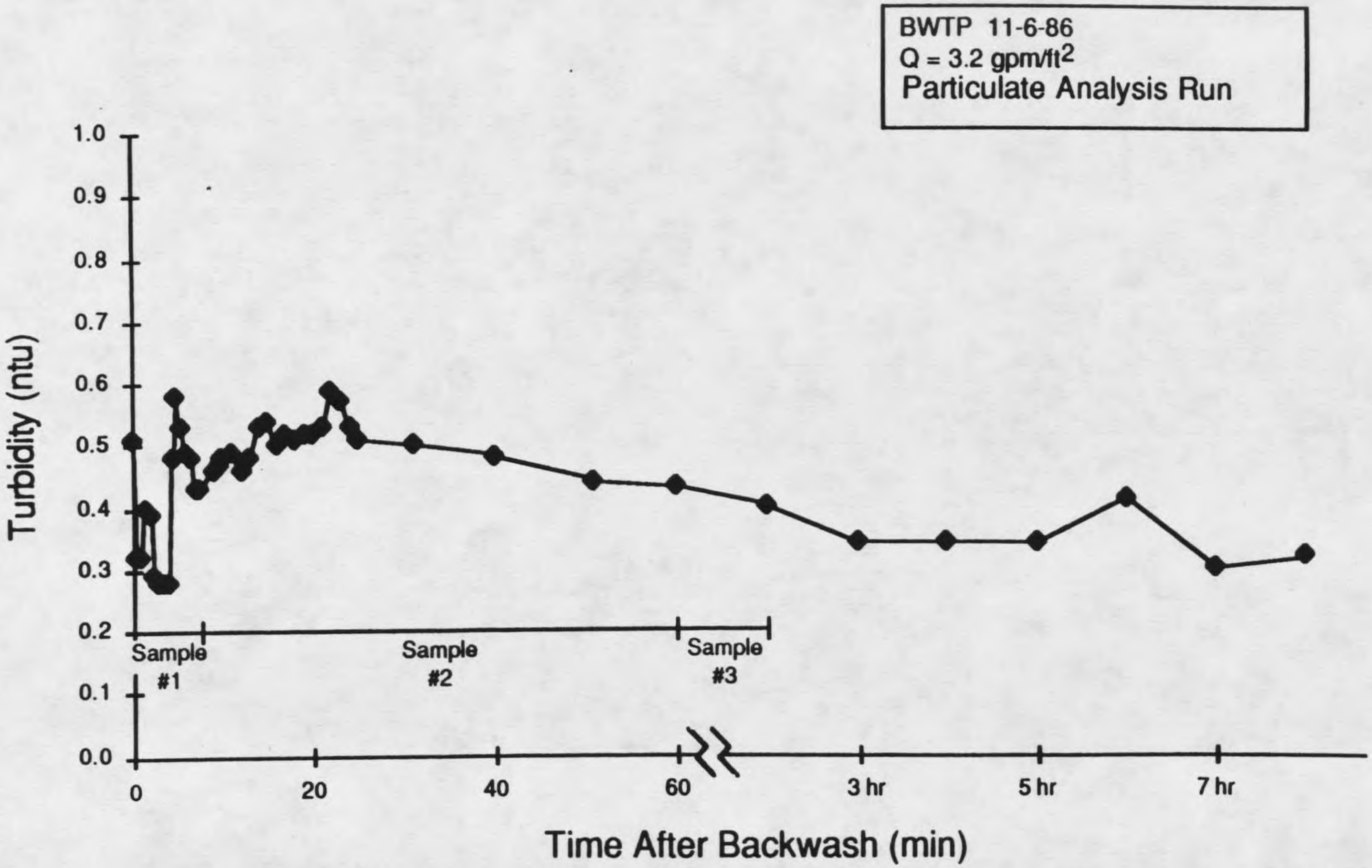

Figure 26. Sampling Times For Particulate Analysis.
Bozeman Water Treatment Plant.

as well as the turbidity spike associated with the filter-to-waste and clear well valves' respective closing and opening. Sample #2 includes the second turbidity peak. Sample #3 includes filter effluent only up to two hours into the filter run. From Figure 26 it can be seen that the effluent turbidities at this point are still quite high; 0.40 ntu.

The results of this particulate analysis agree with all the literature presented in Chapter 3. Firstly, the decrease in effluent turbidity during the post backwash period has been associated in pilot scale studies, with an accompanying decrease in Giardia cyst numbers (Logsdon and Rice, 1985; Al-Ani, et al., 1984).

Secondly, Logsdon, et al. (1985) reported that the Giardia cyst concentrations may be higher than usual during the first portion of a filter run. The cyst-sized particles in the filter effluent during the BWTP particulate study seem to indicate similar results. Even though no cysts were found, the potential for the transmission of Giardia through the filter is largest during the initial stage of the filter run.

Thirdly, several studies have correlated particulate counts with turbidity (McCoy and Olson, 1986; Reilly and Kippin, 1984; O'Connor, et al., 1984). This analysis at the BWTP seems to agree with their findings.

More extensive research on particulate analysis and plant scale studies with non-viable Giardia cysts and cyst-sized particles are necessary for generating firm conclusions.

Bacterial Counts

Both heterotrophic plate counts and total coliforms were enumerated. A trend was seen relating filter effluent turbidities with total coliforms. Heterotrophic plate counts did not show a trend related to turbidity. Chlorinated backwash water played a large role in the numbers of bacteria present in the filter effluent. Raw water bacterial counts varied, and were influenced by seasonal and environmental factors.

Seasonal Variations

Table 17, below, lists all filter runs at both water treatment plants from which bacterial counts were made. Also included are raw water parameters, and a ratio of heterotrophic counts to total coliforms for each filter run. The table shows several trends:

1. The BWTP has the highest heterotrophic plate counts (HPC) in the springtime and summer, lower counts in the fall, and somewhat higher counts again in the winter.
2. The total coliform counts (TC) increase over the year, from springtime to winter.
3. The ratio of HPC/TC is highest in the spring, and decreases through the seasons, to reach the lowest ratio in the winter.
4. The HWTP shows an HPC trend of high summer numbers, even higher counts in the fall, and falling numbers through the winter. Potassium permanganate ($KMnO_4$) was added at the HWTP during runs #33, 34 and 35 due to taste and odor problems and high algal counts. The concentration

Table 17. Bacterial Counts and Raw Water Paramenters.

		Raw Water Quality						
		Standard Parameters			Microbiological Parameters			
Run No.	Date of Run	Turb. (ntu)	Temp. (°C)	pH	Total Coliforms Per 100 mL	HPC Per mL	HPC Per 100 mL	Ratio of HPC : TC Per 100 mL
Bozeman Water Treatment Plant								
1	03-28-86	4.1	6	6.2	110	-	-	-
4	05-04-86	6.1	10	6.1	48	-	-	-
8	06-15-86	5.0	13	6.8	24	290	29000	1208.3
10	06-23-86	2.0	11	6.4	45	950	95000	2111.1
11	07-08-86	0.87	13	6.3	121	245	24500	202.5
14	09-23-86	0.90	7	7.1	85	350	35000	411.3
15	10-05-86	0.98	9	7.2	275	530	53000	192.7
16	10-12-86	0.67	3	6.6	318	80	8000	25.2
18	10-24-86	0.63	4	6.8	334	67	6700	20.1
19	11-01-86	0.63	3	7.0	302	157	15700	52.0
22	11-16-86	0.85	2	7.0	517	210	21000	40.6
23	11-19-86	2.2	2	6.7	382	238	23800	62.3
27	01-14-87	0.65	1	6.5	256	194	19400	75.8
30	01-26-87	1.2	1	6.8	121	46	4600	38.0
Mean	-	1.9	6.1	6.7	209.9	279.8		
Standard Deviation	-	1.8	4.4	0.3	150.7	249.9		

Table 17. (Continued.)

Run No.	Date of Run	Raw Water Quality: Standard Parameters: Turb. (ntu)	Temp. (°C)	pH	Microbiological Parameters: Total Coliforms Per 100 mL	HPC Per mL	HPC Per 100 mL	Ratio of HPC : TC Per 100 mL
Helena Water Treatment Plant								
13	07-18-86	5.0	14	8.3	0.3	243	24300	81000.0
16	08-05-86	2.5	14	7.8	13	353	36300	2715.5
23	08-29-86	2.1	16	7.4	1	250	25000	25000.0
33	10-14-86	3.8	15	8.3	17	3000	300000	17647.1
34	10-17-86	3.7	13	8.4	2100	1619	161900	77.1
35	10-28-86	3.7	13	8.7	23	213	21300	926.1
36	12-19-86	3.7	13	8.5	23	101	10100	439.1
37	12-30-86	1.6	6	8.4	0	127	12700	-
38	01-09-87	1.9	6	8.2	12	55	5500	458.3
39	01-19-87	1.8	6	8.4	14	58	5800	414.3
Mean -		3	11.6	8.2	220.3	601.9		
Standard Deviation -		1.1	4	0.4	660.5	961.6		

of $KMnO_4$ was 2.75 mg/L for runs #33 and 34, and was 1.00 mg/l for run #35. Runs #33 and #34 exhibit very high HPC's and run# 34 shows an extremely high TC count during this period of high taste and odor.

5. Total coliform numbers at the HWTP were lowest in the summer, rose in the fall and early winter, and then were lower again in mid-winter.

6. The HPC/TC ratio at the HWTP was sporadic. However, a generalization is that the ratio is highest in the beginning of the summer, and decreases as the year goes on.

The two plants' raw water sources are very different. Average turbidity, temperature, and pH of these waters are dissimilar. However, a general trend is that; (1) HPC is highest in the spring and early summer, decreasing as the year passes, (2) TC's are lowest in the early part of the year, and increase over the seasons, and (3) the HPC/TC ratio is greatest in the early part of the year, and decreases as the year goes by.

Environmental factors play a large role in the injury, and subsequent enumeration of organisms (LeChevallier and McFeters, 1985). The HWTP's raw water source has more opportunities for injury to organisms, therefore, it is not surprising that the total coliform counts for this plant are much lower than for the BWTP. The reservoir probably plays a large role in the injury to the coliforms and in the heterotrophic bacterial numbers.

First, the reservoir's detention time is highly variable, depending on the irrigation needs of the Helena Valley farmlands. Coliform viability, and thus detection, is limited to about one week outside its source (the intestinal tract of animals). During periods of low water use by irrigators, the detention time in the reservoir would increase, causing the coliform counts to decrease. Also, as the detention time of the reservoir increases, the heterotrophic organisms may multiply. High HPC's (500-100/mL) may cause the coliform counts to be lower (LeChevallier and McFeters, 1985).

Secondly, the reservoir is a relatively warm raw water source for the HWTP. This fact, combined with the nutrients available in the reservoir, intensify the heterotrophic bacterial growth rate.

Thirdly, prechlorination of the water as it enters the water treatment facility enhances the injury to the organisms. It is safe to assume that there could be some effect upon bacterial counts during the times when the HWTP must treat the water with $KMnO_4$. The author would tend to assume a negative effect on the bacterial counts upon the addition of the potassium permanganate. However, the three bacterial counts made during application of this chemical seemed to indicate the opposite effect.

The Bozeman Water Treatment Plant, on the other hand, can expect fewer injured organisms. The raw water sources are cold running streams, which travel from the source to the water treatment plant in only 2 to 3 hours. Importantly, the raw water is not prechlorinated.

As a matter of fact, the coliform counts were higher at the BWTP. In addition, the counts of both HPC and TC's were less variable at the BWTP than those of the HWTP. Without examining each treatment plant's specific raw water sources, and investigating all the variables associated with them, the exact reason for these differences are unknown. However, when the sources are compared in terms of opportunity for injury to the bacteria, it logically follows that:

1. The HWTP's HPC and TC counts will vary greatly over the course of the year, even within seasons.
2. The BWTP will have higher coliform counts than the HWTP.
3. The BWTP bacterial counts will be less variable than the HWTP's.
4. The HWTP will have higher HPC counts than the BWTP.

These logical deductions are borne out with the available data.

Total Coliforms

Total coliforms were enumerated on MT-7 and m-Endo media. MT-7 gave consistently higher counts during the post backwash period. The largest difference in counts yielded on MT-7 as compared to m-Endo was 151 times at the HWTP, and 58.6 times at the BWTP. The average difference was 4.8 times higher counts on MT-7 than on m-Endo at the BWTP, and 12.8 times higher at the HWTP.

Figures 27 through 32 illustrate representative total coliform analyses made at both the BWTP and the HWTP. The balance of the coliform analyses can be seen in the Appendix below. Total coliform counts are shown on both MT-7 and m-Endo agar, along with turbidity vs. time after backwash.

The general trend was that the MT-7 agar yielded higher counts than m-Endo through the filtration of the backwash water remnants. Often, samples on m-Endo agar would exhibit no growth until the one filter

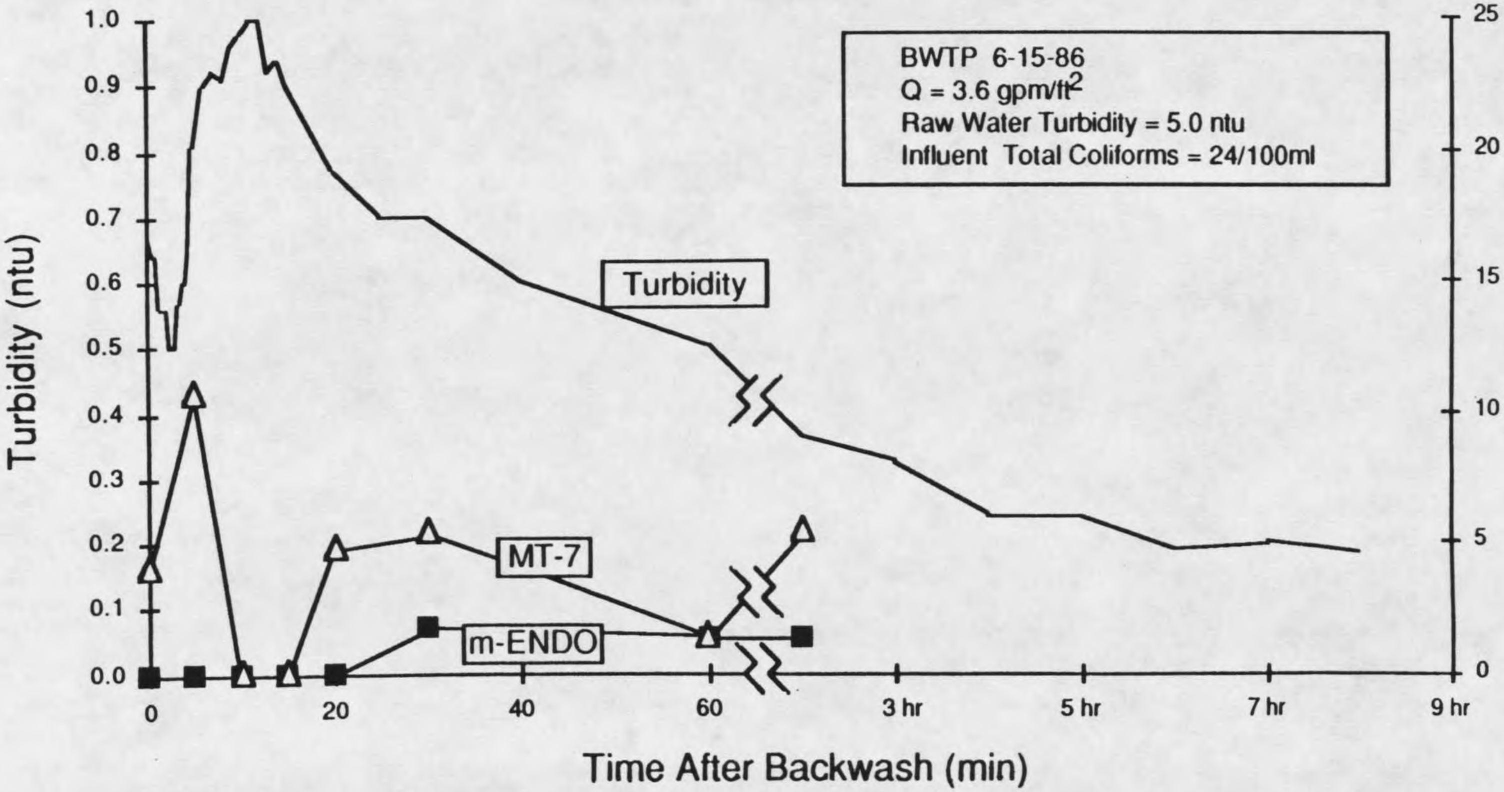

Figure 27. Total and Injured Coliform Levels During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 11.6 min.

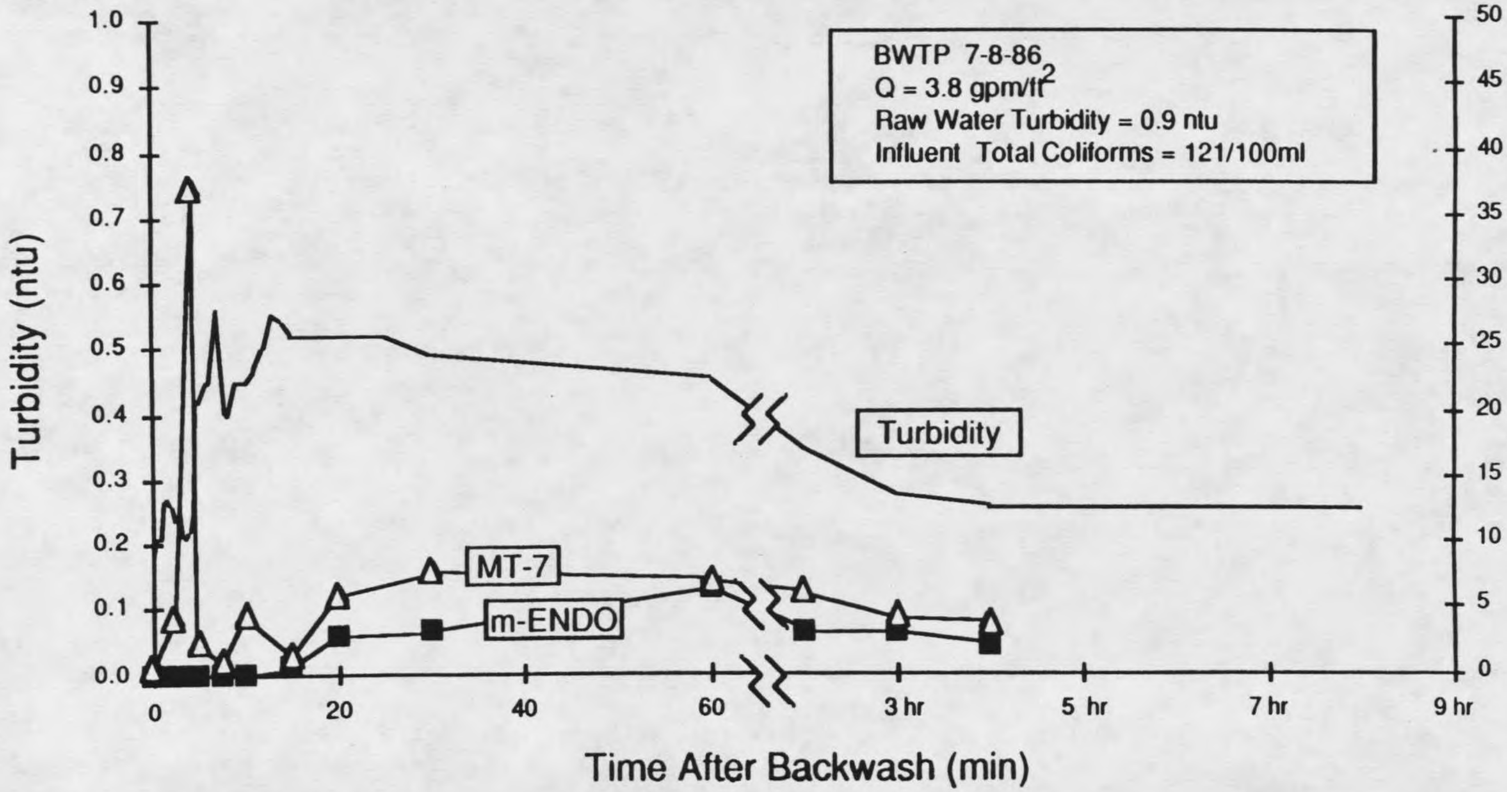

Figure 28. Total and Injured Coliform Levels During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 11.0 min.

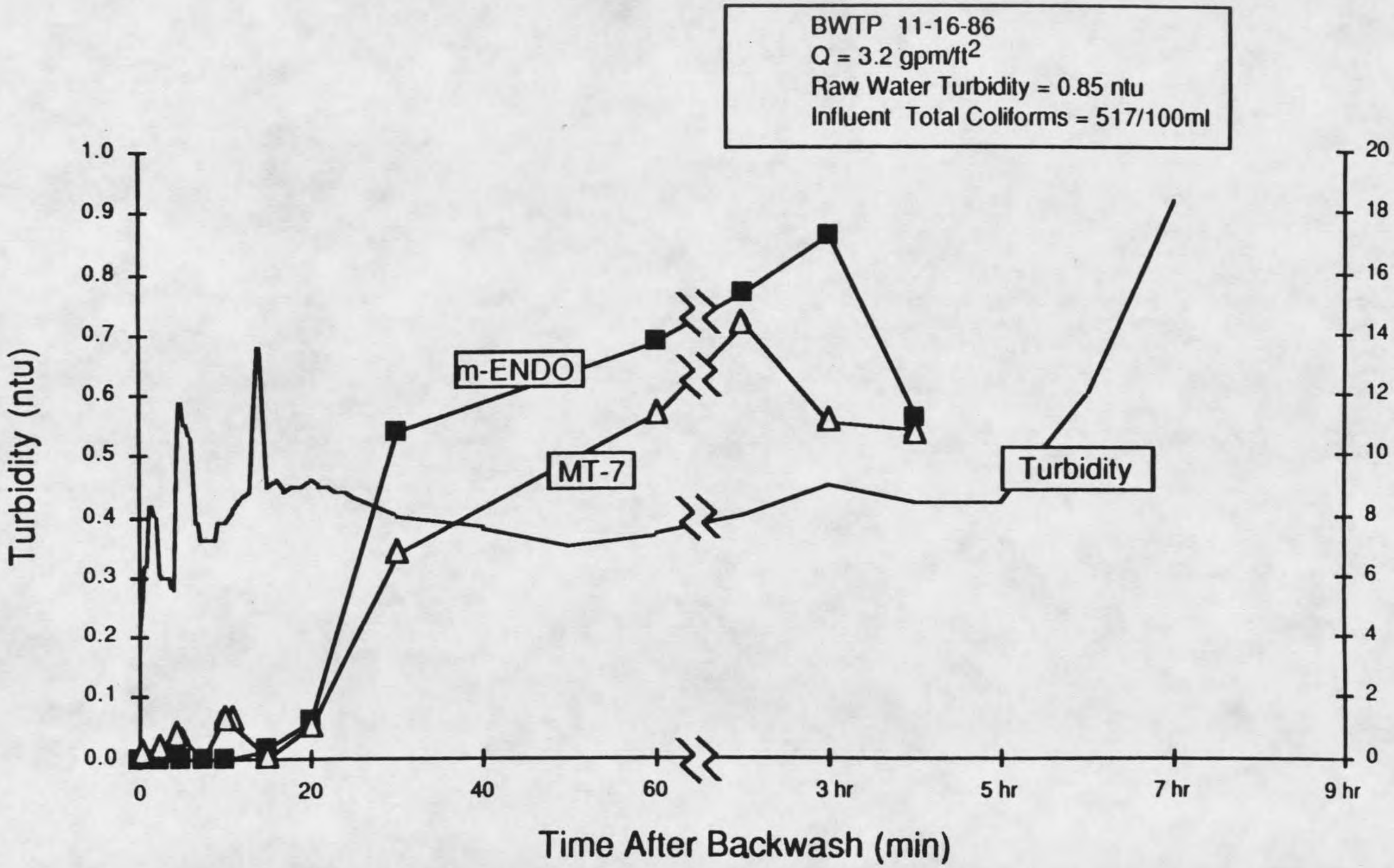

Figure 29. Total and Injured Coliform Levels During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 13.1 min.

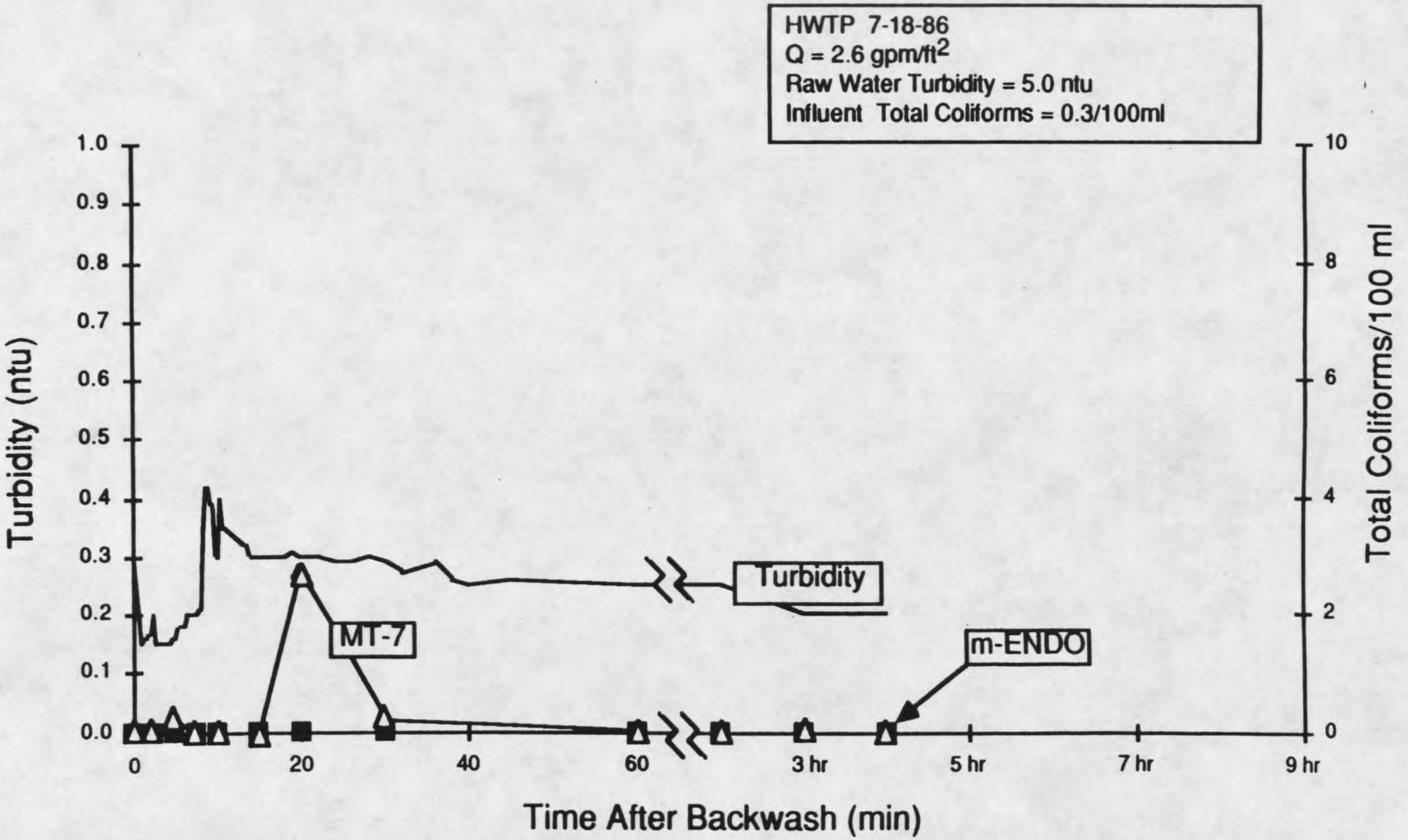

Figure 30. Total and Injured Coliform Levels During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

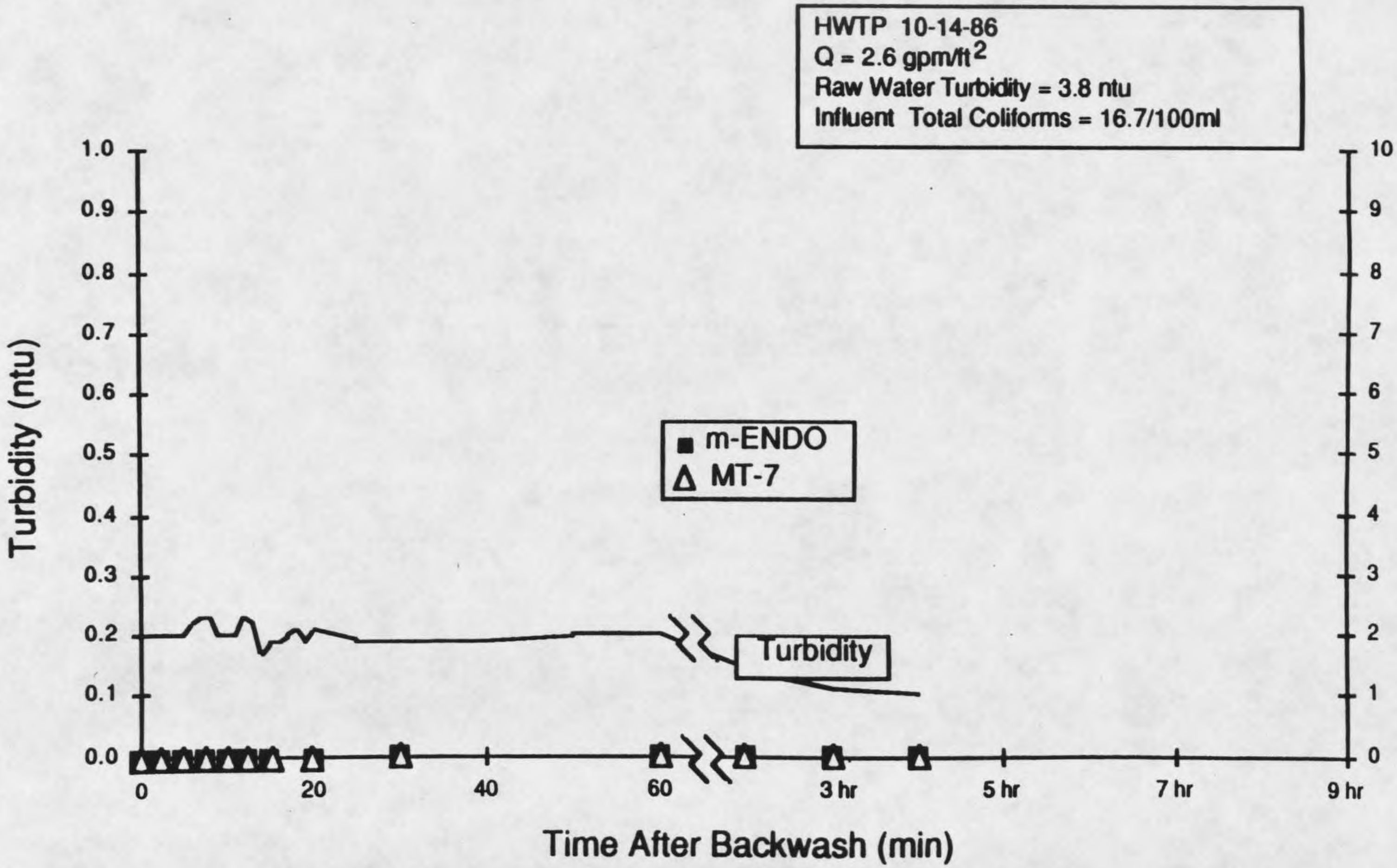

Figure 31. Total and Injured Coliform Levels During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

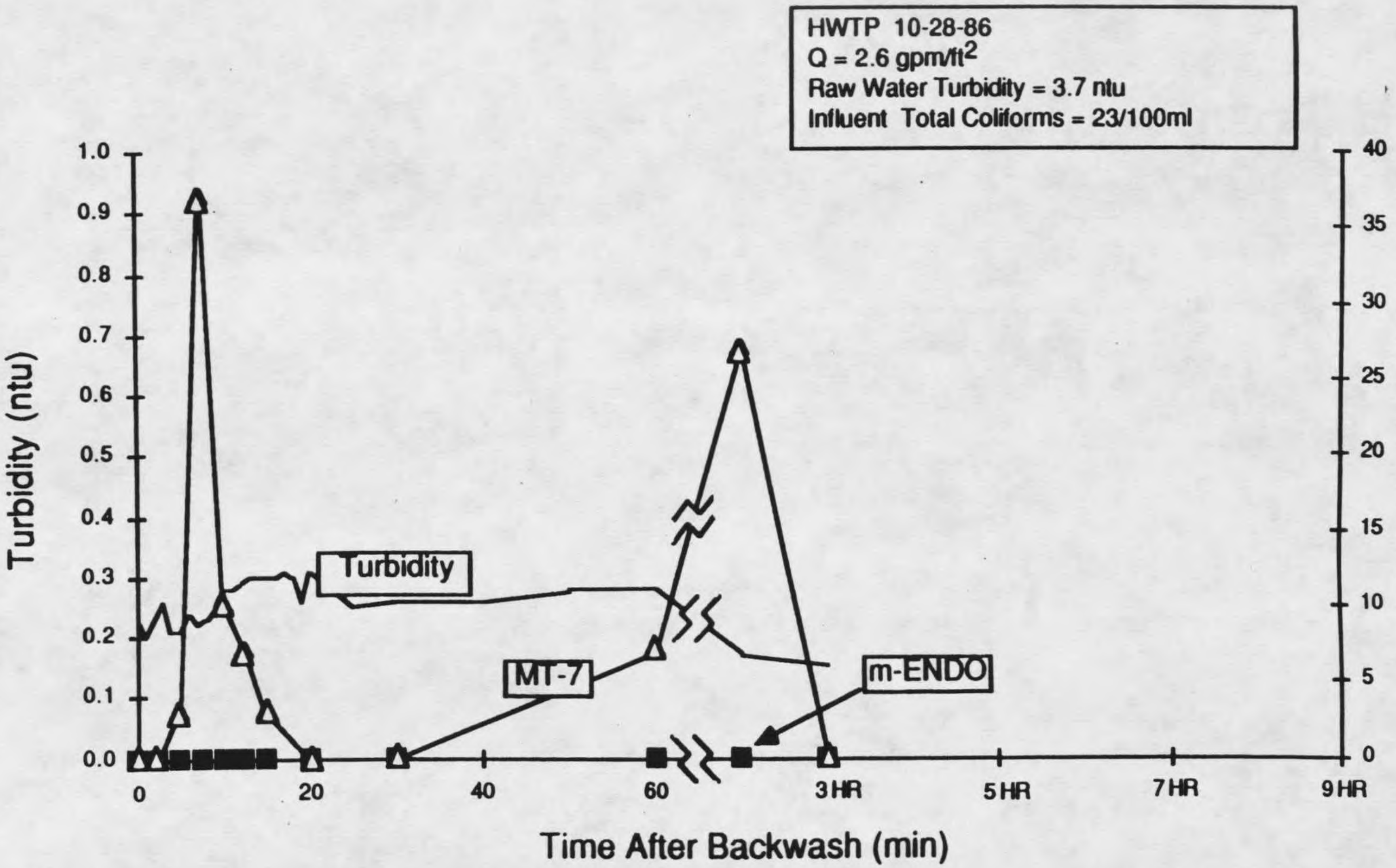

Figure 32. Total and Injured Coliform Levels During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

detention time into the filter run. The obvious cause is chlorine injury to the coliforms associated with the backwash water remnants. Once the filter began to filter the influent, the counts were usually similar. Over the sample period, 0 minutes to 4 hours after backwash, bacterial counts were lower during the initial filter effluent degradation period, and would rise to a semi-constant level after 60 minutes to 2 hours following backwash.

The highest coliform counts during the filtration of the backwash water remnants occurred at the point when the filter-to-waste valve closed and the clear well valve opened, ie. the time of the turbidity spike, in the BWTP. At both water treatment plants, high coliform counts occurred at the beginning of filtration of influent, ie. one detention time after backwash, or occasionally, at 0 minutes after backwash, ie. upon the opening of the filter effluent valve.

Two filter runs at the HWTP yielded no coliforms at any of the sample times (Figure 31 and see the Appendix). These filter runs received the highest dosages of $KmnO_4$ recorded for this study: 2.75 mg/L. PAC and alum concentrations were also higher than average on those days. Other than that, there are no other unusual parameters. The filter run pictured in Figure 30 is fairly average in all the parameters recorded. It is not clear why no coliforms were detected in the filtrate for the filter run in Figure 31 and the filter run of 10-17-86, pictured in the Appendix, especially since the influent coliform counts were 17/100 mL and 2100/100 mL, respectively. The count of

2100/100 mL is strange, and is suspect. The heterotrophic plate count for that influent was 1619/mL (Table 17).

High coliform counts have been reported to occur immediately following a backwash, and to be related to turbidity in studies carried out with pilot scale filters. The data gathered here indicate that this may be true in a full scale plant also, but the relationship is distorted due to the effects of chlorinated backwash water. Assuming that the coliforms present in the filtrate associated with the backwash remnants were accumulated in the filter media during the previous filter run (that is, that they did not originate from the backwash water itself), and if they remained within the filter bed during the entire backwash cycle, then they would have been exposed to chlorine for a minimum of twenty minutes. Also, if the same coliforms were associated with the backwash water remnants remaining above the filter bed after the backwash, they would appear in the filter effluent near the one detention time mark. Thus, to be enumerated, they would have been exposed to chlorine concentrations of 1.4 to 1.5 mg/L for 30 to 35 minutes. Hence, the backwash probably kills most of the coliforms present in the backwash water remnants.

The three times at which the post backwash coliform counts were highest can be attributed to coliforms which are not associated with the backwash water remnants:

1. Coliforms which appear in the filter effluent at 0 minutes after backwash may be due to organisms colonizing the filter effluent pipework in biofilms. Work done by researchers investigating distribution

systems indicate that a variety of organisms establish ecosystems within pipework. Since the BWTP does not prechlorinate, it is very possible that there is a certain amount of biological growth within the filter effluent pipework. Even with prechlorination, the possibility still exists. Pre-filter free chlorine concentrations at the HWTP average 0.09 mg/L. Ridgway and Olson (1982) and Reilly and Kippin (1983) in their studies of distribution systems, have determined that colonization of pipes was occurring under free chlorine residuals of 0.5 to 1.0 mg/L free chlorine. It is believed that encapsulation plays a major role in protecting the bacteria from the chlorine.

As the filter effluent valve opens, following a backwash, the biofilms lining the pipes are put under a certain amount of shear stress from the sudden flow through the pipes. Some of the bacteria may be loosened from the biofilm, and thus appear in the filtrate.

2. The bacteria which appear in the initial stage of filtration at the BWTP, coinciding with the 4.5 to 5 minute turbidity spike, are most likely set free from filter media by the same mechanisms which cause the turbidity. Work by Camper, et al. (1987), and LeChevallier, et al. (1984), indicates that heterotrophic plate count bacteria and coliforms are attached to granular activated carbon. Their work indicates that operational variables, such as changes in filtration rates and sudden increases in turbidity applied to the filter can lead to the release of populated fines into the filtered water. The effect was greatest with GAC, but the effect is also seen with anthracite and sand. The bacteria associated with carbon particles were highly resistant to chlorine.

3. The occurrence of coliforms in the filter effluent one detention time following backwash is common to both water treatment plants. This is not surprising, since these organisms are exposed to no (BWTP) or little (HWTP) chlorine, and they are travelling through the filter at the time when the filter is the least efficient.

Heterotrophic Plate Counts

Heterotrophic plate counts (HPC) were highly variable. In general, the HPC's were much more sporadic, and showed much more variability in numbers than the total coliform counts. Counts varied from 0 to 1430 organisms / mL in filtered water. High HPC's were most often seen at the detention time of the filter following backwash.

Figures 33 to 38 are the HPC and turbidity vs. time graphs of representative filter runs from the Bozeman and Helena water treatment plants. The balance of the filter runs can be seen in the Appendix below.

The HPC's are much less predictable than the total coliforms. Also, there is no relationship between HPC and turbidity.

Chlorine plays a large role in the occurrence of bacteria in the initial filter effluent. The influence is both direct and indirect. The direct role is to kill and injure bacteria through the contact time afforded by the backwash itself, and through the filter detention time, as the backwash water remnants are filtered. This is an important barrier to the transmission of bacteria and other organisms through the system. The indirect role which chlorine plays is the selection of chlorine resistant bacteria, and the determination of the location the bacteria will eventually come to colonize, such as the biofilms lining pipework and the colonization of granular activated carbon particles.

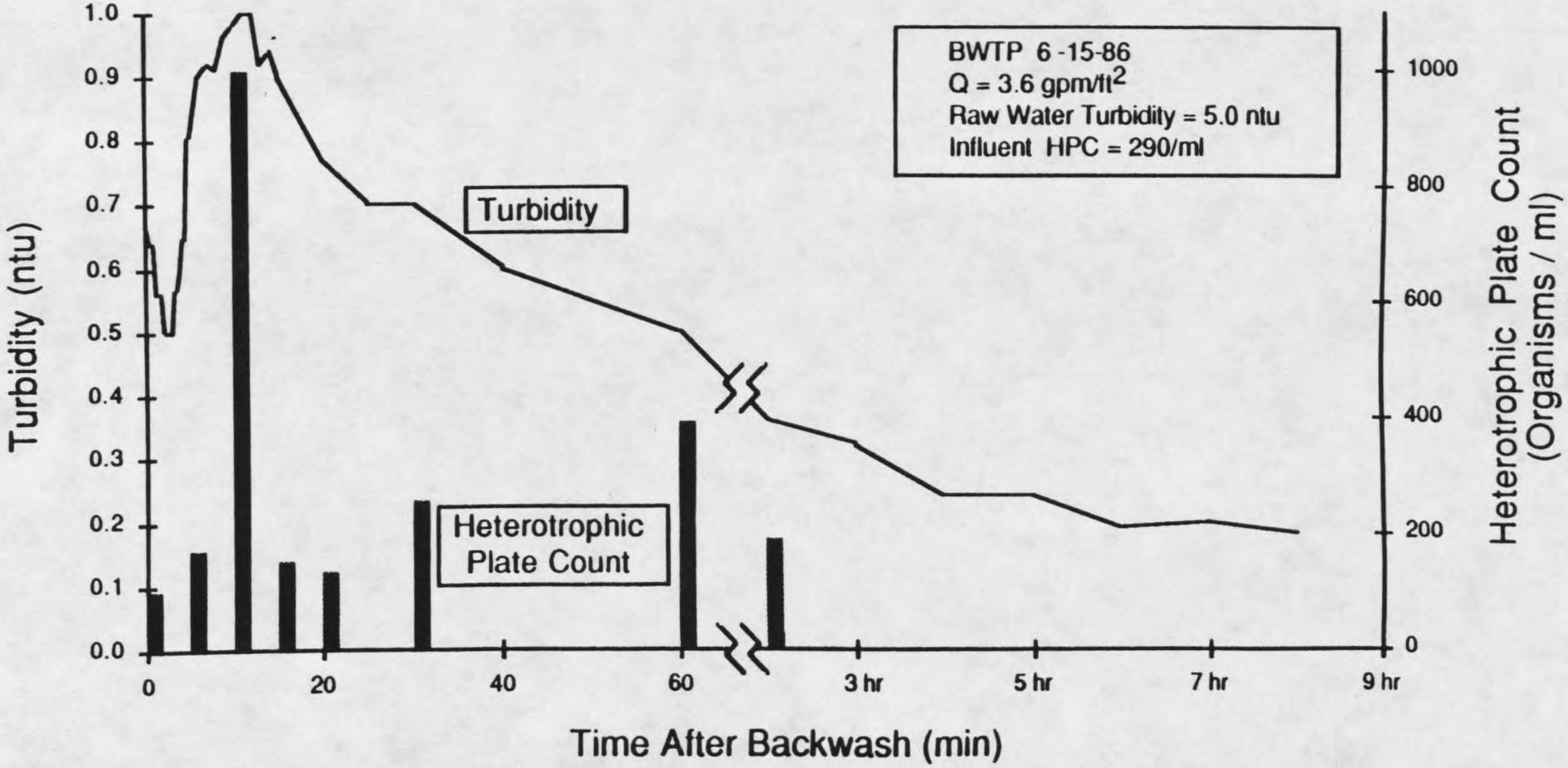

Figure 33. Heterotrophic Plate Counts During Initial Filtration. Bozeman Water Treatment Plant. Filter detention time = 11.6 min.

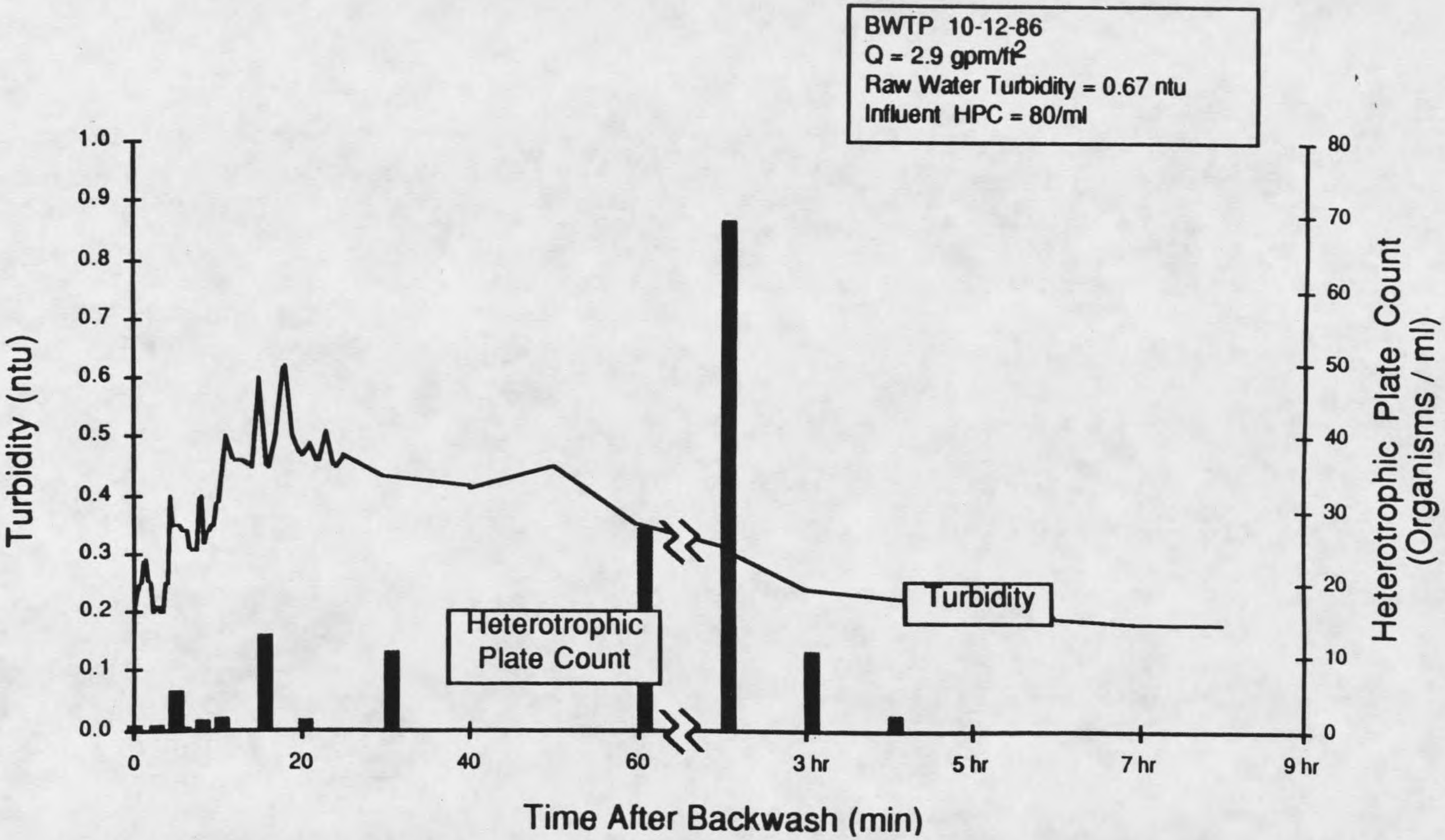

Figure 34. Heterotrophic Plate Counts During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 14.4 min.

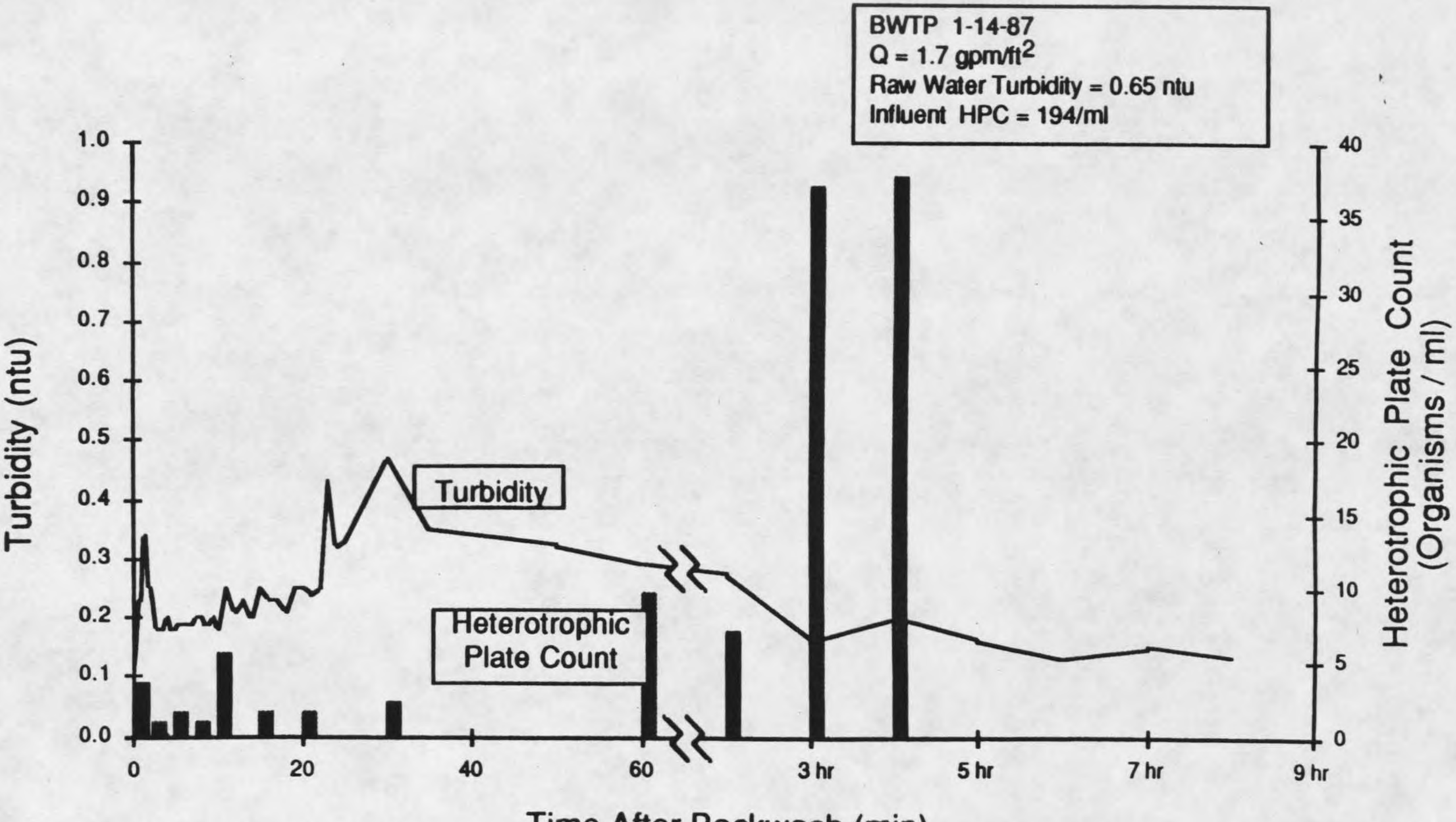

Figure 35. Heterotrophic Plate Counts During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 24.6 min.

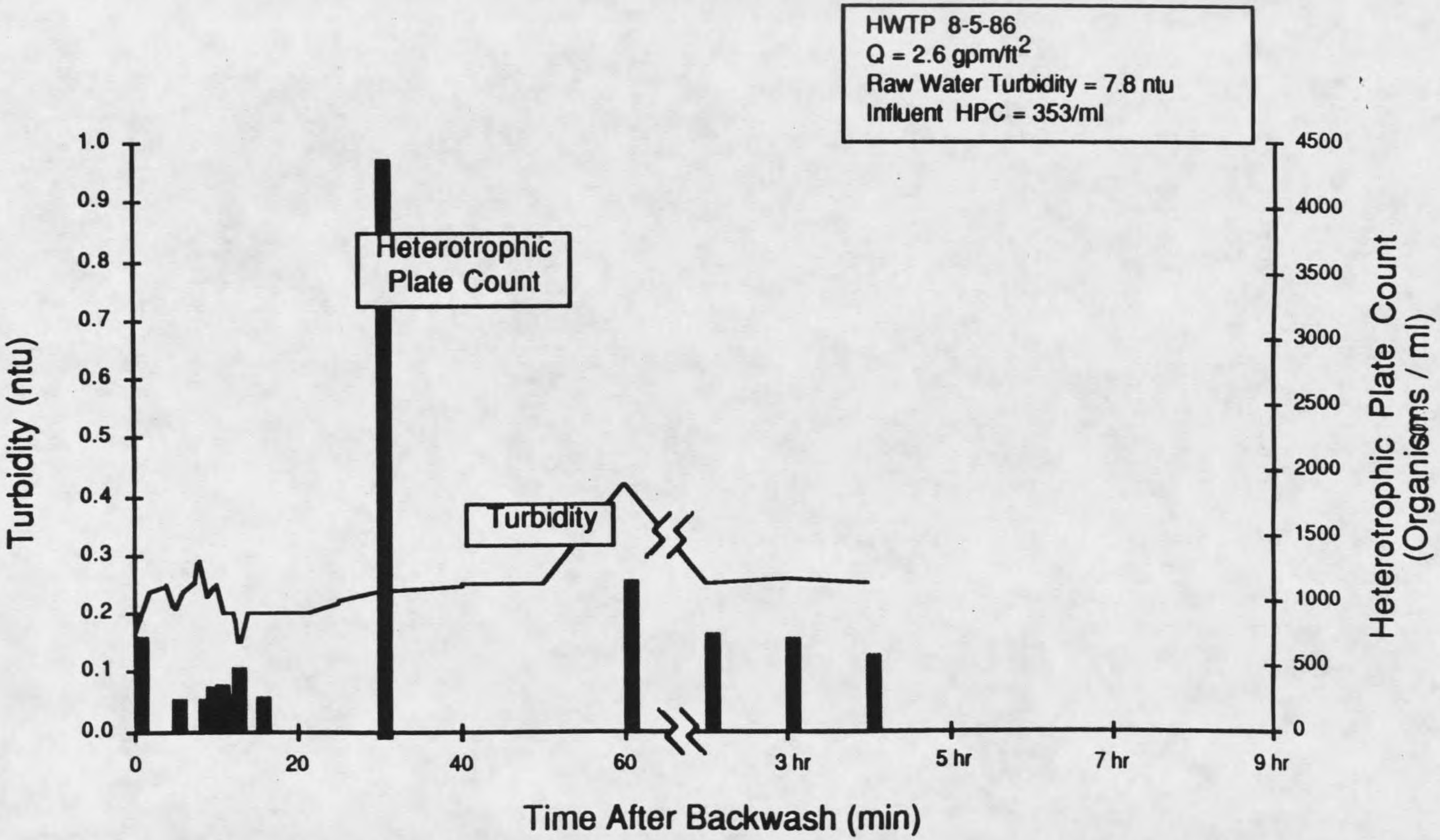

Figure 36. Heterotrophic Plate Counts During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

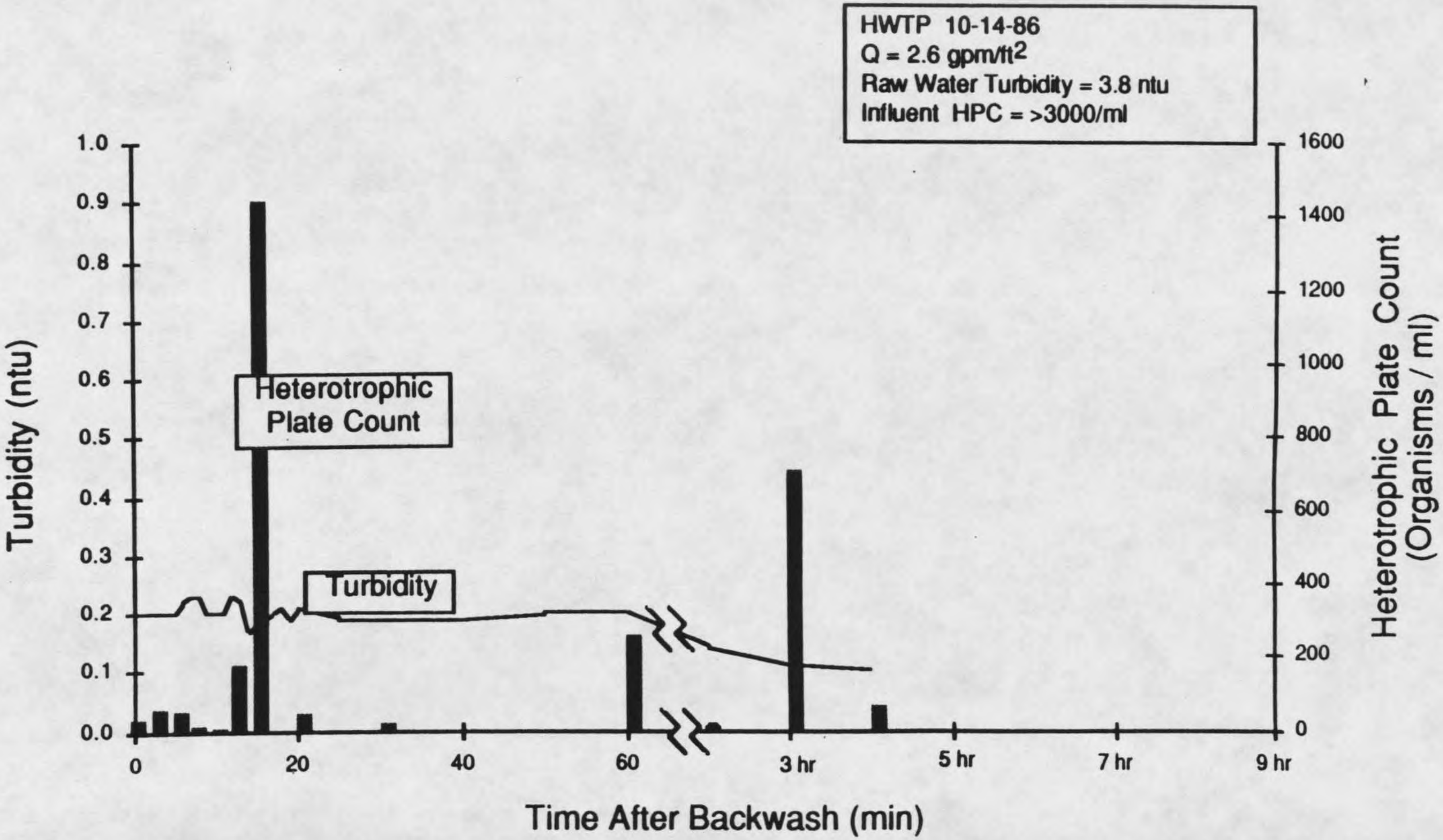

Figure 37. Heterotrophic Plate Counts During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

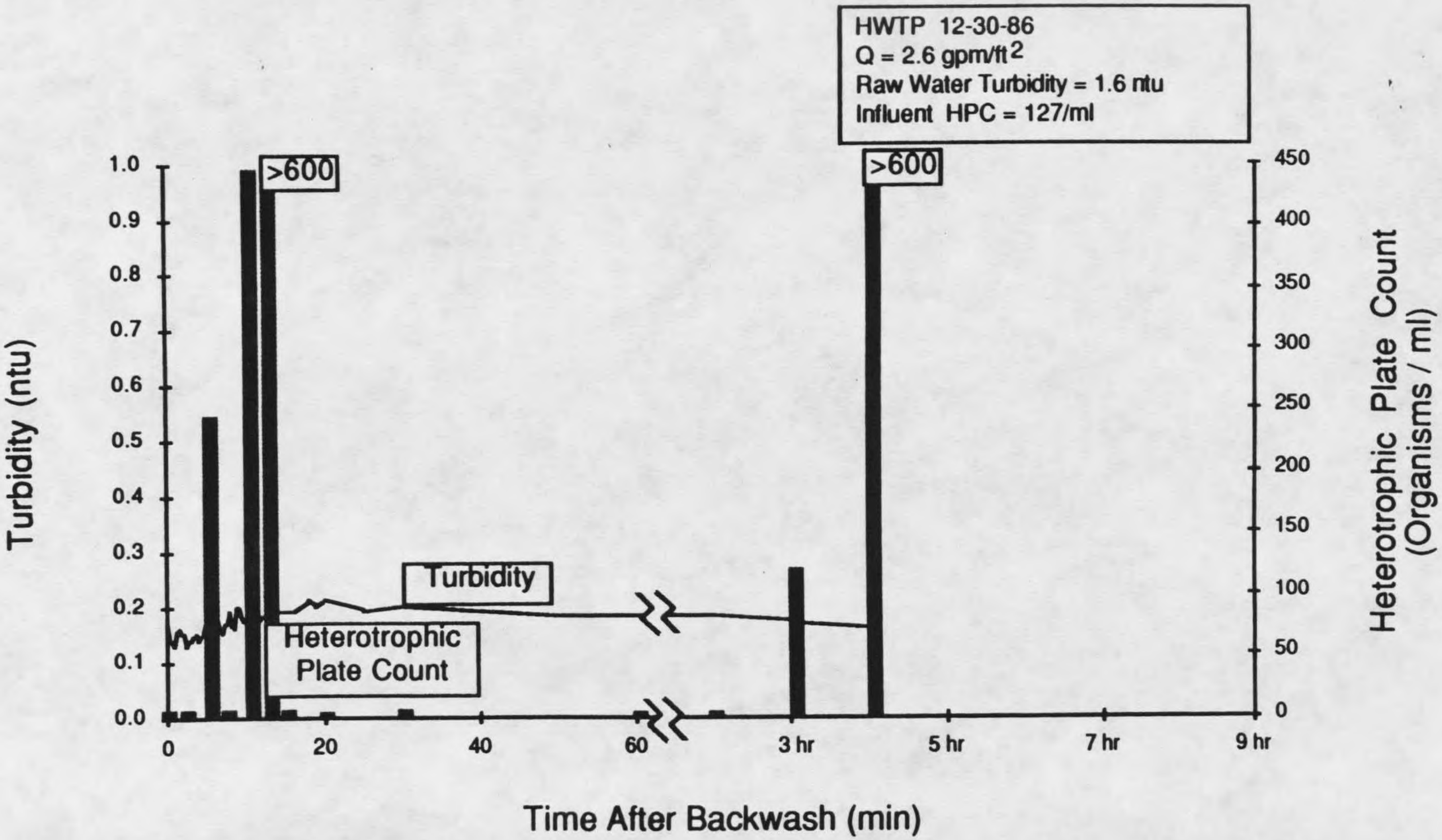

Figure 38. Heterotrophic Plate Counts During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

CHAPTER 6

CONCLUSIONS AND SUMMARY

This research has provided insight into the characteristics of the period of filtration following a backwash under "real", as opposed to pilot plant conditions. Since it is this portion of the filter run which is considered to be the most important in terms of health and water quality standards, it is vital that it be well understood. The extent to which the post backwash phase of filtration is not understood can be illustrated by the Bozeman Water Treatment Plant's filter-to-waste period, which wastes water of higher quality (turbidity and bacteriologically speaking) than is kept, and due to the hydraulic design, actually decreases the water quality of the initial filter effluent. A design such as that is probably due to the blind inclusion of a filter-to-waste period without any understanding of either the characteristics of the period, or exactly what is hoped to be gained for the inclusion of this procedure. The Helena Missouri River Water Treatment Plant, on the other hand, is not designed with a filter-to-waste period, and the water quality does not ever exceed water quality standards.

Whether or not the inclusion of a filter-to-waste period is prudent as part of the initial stage filtration following a backwash is very plant specific. The post backwash turbidity profile of each filter will vary, depending on a myriad of factors including raw water turbidity and other characteristics, chemical treatment prior to filtration, the design of the filter unit, and the filter flow rates used. What this study has accomplished is the definition of general characteristics of the post backwash period based on water treatment plant conditions. The application of the filter-to-waste procedure can then be evaluated, and an informed judgement can then be made concerning the advisability of this procedure.

Some general conclusions concerning the post backwash period of filtration:

Turbidity

A dual peak turbidity characteristic can be expected in the post backwash period. The first turbidity peak occurs within the first few minutes of filtration, and varies in magnitude. The magnitude of this turbidity peak is often small in comparison to the total initial filter effluent degradation, and varies according to season and to raw water parameters. This turbidity is associated with the backwash water remnants.

The second turbidity peak occurs at one detention time (the time it takes the water to flow through the filter unit) and thus is associated with the filter influent, as the backwash water remnants disperse. In Cranston's study, using a pilot scale filter unit, this turbidity peak occurred at exactly one detention time. In a real system this peak tended to occur at or very near one detention time. The reason for the difference is twofold: (1) Grab samples were used to measure turbidity, and were taken at one minute apart at the times at which the detention period was occurring, and (2) filters in a full scale plant will be less ideal in terms of a plug flow reactor model than will a pilot scale filter.

Grab samples, due to their instantaneous nature, have a disadvantage in that they may not be as accurate a measure of a peak than is a continuous sample. If for example, a sample's turbidity at 15 minutes was 0.65 ntu, and the sample taken at 16 minutes was read at 0.67 ntu, then the 16 minute sample was used as the peak reading. If the detention time was calculated to occur at say, 15.1 minutes, then the grab sample may have missed the peak reading.

A second source of variation is the character of the filter unit itself. The influent to a filter unit may not be dispersed well over the entire surface of the filter, and thus will filter unevenly. The mixing which occurs as the filter influent meets the backwash remnants standing above the filter media, and the placement of the influent pipe can influence the characteristic of the post backwash filter effluent profile. Thus the time at which the second turbidity peak occurs is dependent on the filter's behavior as a plug flow reactor.

The magnitude and the duration of the second turbidity peak is dependent upon the filter flowrate and the influent turbidity. At similar flow rates, the filter influent with the highest turbidity will produce a second turbidity peak with a shorter duration. With similar turbidities, the filter with a higher flow rate will recover more quickly.

Particle Counts

Particle count trends may be a good measure of the general turbidity trends of the post backwash period. Only one particle count was done in conjunction with this study. Results however, agree with those found in the literature. The occurrence of Giardia sized particles was greatest during the first portion of the filter run (0 to 7.5 minutes), and decreased from 8.5 to 60 minutes. From 60 to 120 minutes (no samples were taken after 120 minutes) the removal of particulates was very efficient.

Bacterial Counts

Seasonal variations in the raw water bacterial counts affect the filter effluent counts, in terms of relative numbers and types of bacteria found. Similarly, the raw water and filter effluent bacteriological characteristics vary depending on source. Even though the raw water source for each of these water treatment plants is very different, the general trend seemed to be that the ratio of heterotrophic plate count to total coliforms found was highest during the spring and summer, and decreased as the year progressed.

Total coliforms were enumerated on both m-Endo and MT-7 agar. MT-7 gave consistently higher counts during the post backwash period than did m-Endo, indicating high numbers of injured organisms. This difference was the most pronounced for samples taken from the newly backwash filter at times preceding the one detention time for that filter. The explanation is that the backwash water remnants are exposed to chlorine for the entire backwash cycle, in addition to the time which it takes for the remnants to filter through as effluent. Thus contact time for the bacteria is from 20 to 30 minutes at chlorine concentrations of 1 to 2 mg/L free chlorine.

The highest coliform counts during the post backwash period occur at three main times, although each filter run may or may not exhibit high counts at all three of these times. They are:

1. 0 minutes after backwash. Possibly there are bacteria colonizing the filter effluent pipework which as the filter effluent valve is opened are sheared from the pipes.

2. At the Bozeman Water Treatment Plant there is often an increase in the numbers of bacteria in the filter effluent as the filter-to-waste valve closes and the clear well valve opens. Other studies (Camper, et al., 1987) have found that sudden rate changes can cause the release of populated fines into the filter effluent, raising the heterotrophic and coliform counts.

3. The most common time at which high bacterial numbers are seen in the filter effluent following backwash is the time which it takes the new filter influent to displace the backwash water remnants. The reason is twofold: 1) The backwash water remnants are chlorinated, reducing bacterial counts, while the filter effluent may be chlorine free (Bozeman WTP), or have a very low chlorine free residual (Helena WTP), and thus may have higher counts. 2) The initial stages of filtration, according to O'Melia and Ali's dendrite and particle accumulation theory, is less efficient than filtration later in the filter run, and will allow passage of more particles, including bacteria.

Heterotrophic plate counts were more variable than were total coliform counts during the initial stages of filtration following backwash. High Heterotrophic Plate Counts were most often seen at the detention time of the filter.

Chlorine plays a large role in the occurrence of bacteria in the filter effluent following a backwash. The direct role is to kill and injure bacteria, preventing transmission through the system. Indirectly, chlorine plays a role in the selection of chlorine resistant bacterial strains.

Summary

In summary, a filter-to-waste procedure is only of value if; 1) the post backwash characteristics for a particular system are understood, and, 2) there are clear objectives for the use of the filter-to-waste period in terms of what exactly is to be accomplished. The elimination of high turbidity levels may or may not coincide with high bacterial counts. Whether the goal of the filter-to-waste period is the reduction of the total turbidity levels, the minimalization of bacterial numbers, reduction of particles present, or elimination of turbidity peaks, must be defined.

Our studies have shown that the use of chlorinated backwash water, proper chemical pretreatment of filter influent, and the avoidance of sudden flow rate changes may actually contribute more to the production of high quality water than does the inclusion of a filter-to-waste period. One parameter which should be investigated in full scale water treatment plants is the post backwash particulate profile. The inclusion of a filter-to-waste period in the first few minutes of a filter run may have some merit for the reduction of particulates during this period. It should be noted, however, that the sudden rate changes caused by the filter-to-waste period may, in fact, increase the particulate numbers. We have found that this is indeed the case with the turbidity, total coliform and heterotrophic plate counts.

The question of exactly where or at what point in time the filter-to-waste period should be initiated, and how long the water will be wasted are important. Much of the time, elevated turbidity readings and bacterial counts occur at one detention time into the filter run, that is, as the filter begins to filter the influent water. It is probably not extremely practical or practicable to filter-to-waste starting at about 10 minutes into the filter run, filtering-to-waste for the next 15 to 20 minutes or so.

Therefore, the recommendation of this author, based upon a year's study of the post backwash characteristics of two water treatment plants in Montana, is that the high turbidity and bacterial counts associated with the post backwash period can be more effectively minimized by the manipulation of treatment variables than by the inclusion of a filter-to-waste period. Important particularly, in the production of a high quality water is elimination of all sudden flow rate changes/increases. The proper pretreatment of the filter influent, as well as the addition of a coagulant to the backwash water (Cranston, 1987) are other important measures to be taken.

In general, a filter-to-waste period may be unnecessary for most water treatment facilities. The control of flowrates and chemical treatments plus maintenance of proper free chlorine residuals in the backwash water is an alternative. This approach to the control of the post backwash period has the advantage of adaptability to various flowrate and raw water characteristics, and, at the two water treatment plant studied here, would be the most attractive alternative for providing the highest quality of water during the post backwash period.

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APPENDICES

APPENDIX I
ADDITIONAL FILTER RUNS WITH TOTAL COLIFORM COUNTS

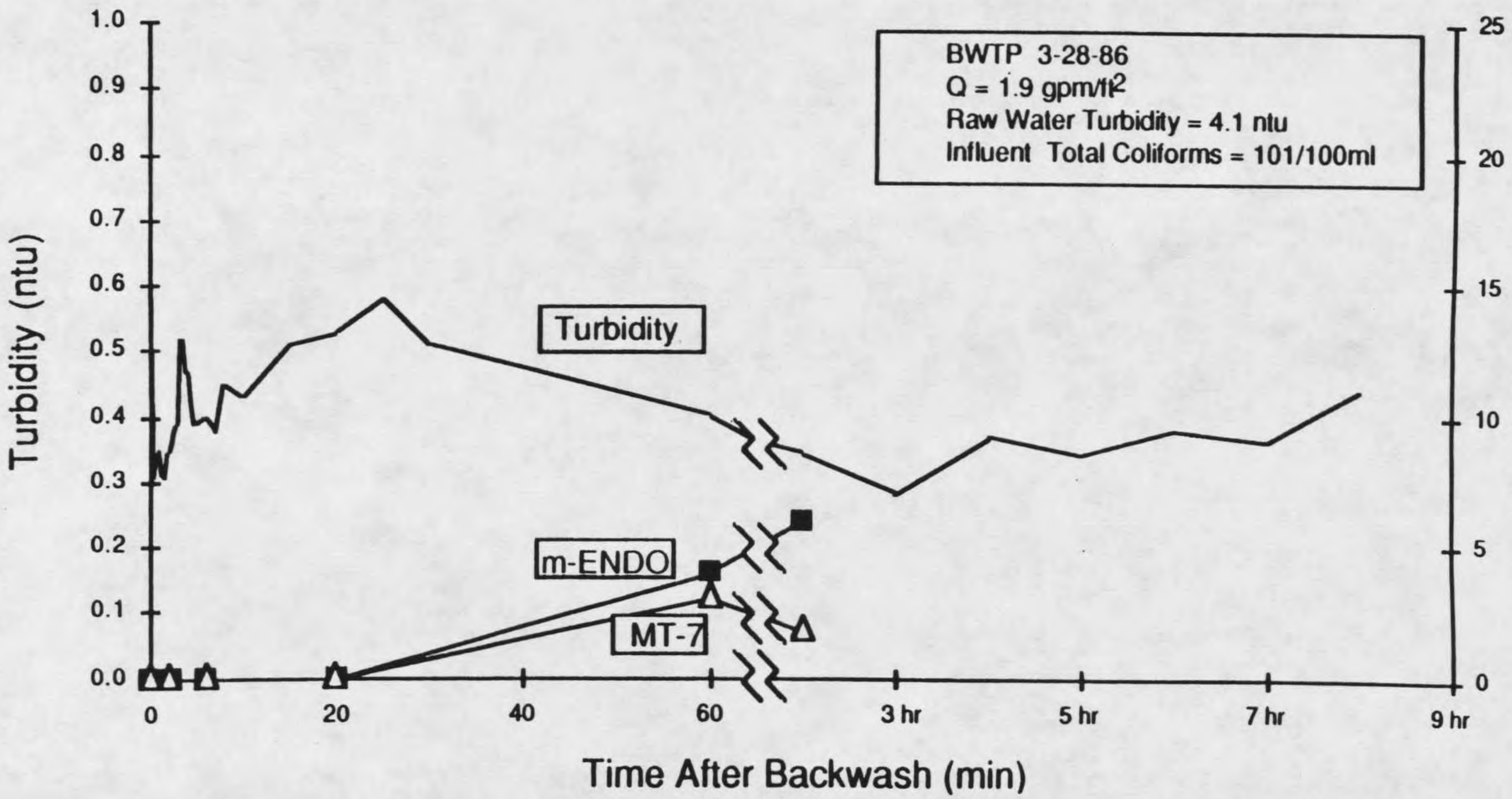

Figure 39. Total and Injured Coliform Levels During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 21.9 min.

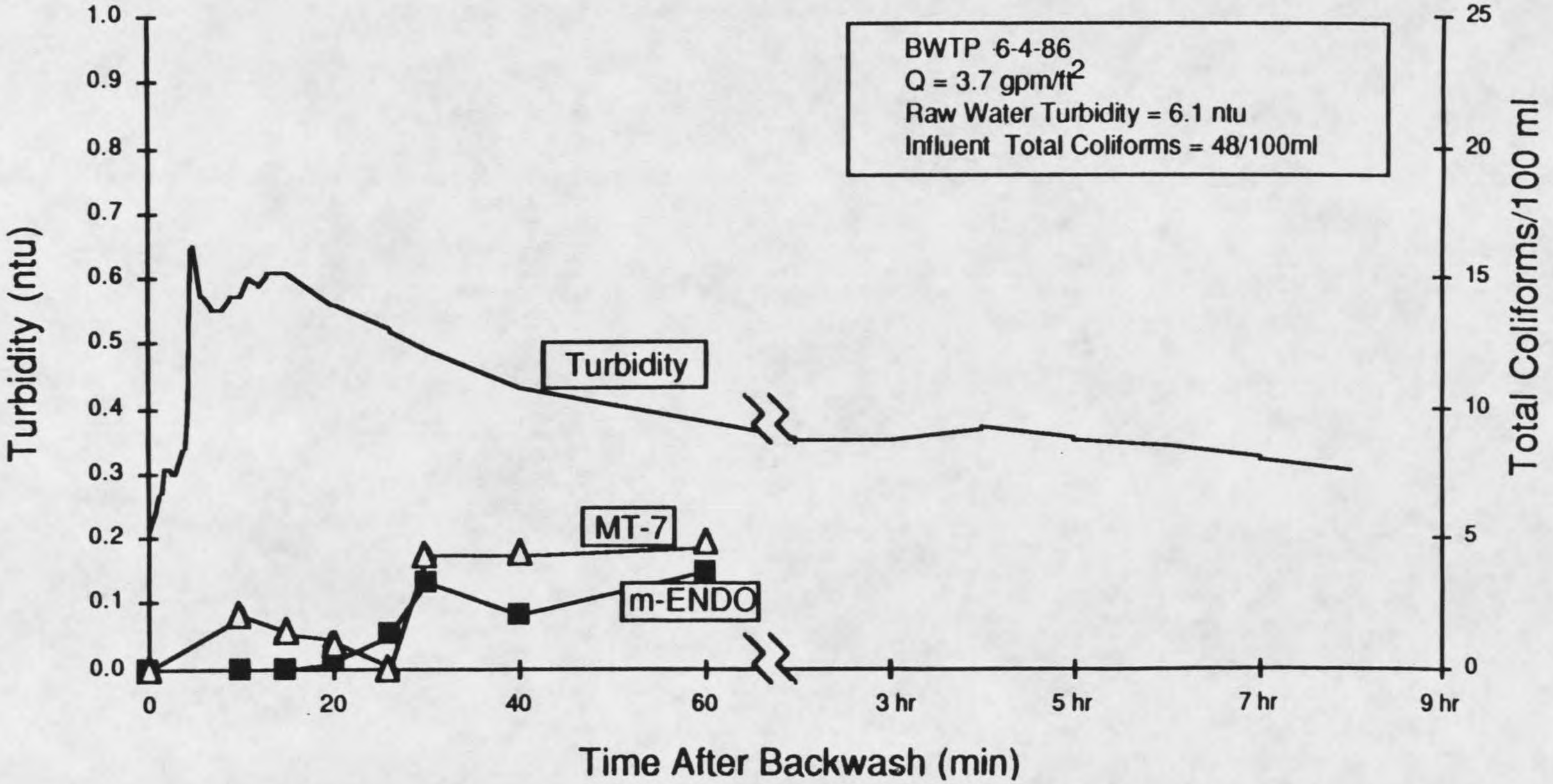

Figure 40. Total and Injured Coliform Levels During Initial Filtration. Bozeman Water Treatment Plant. Filter detention time = 11.3 min.

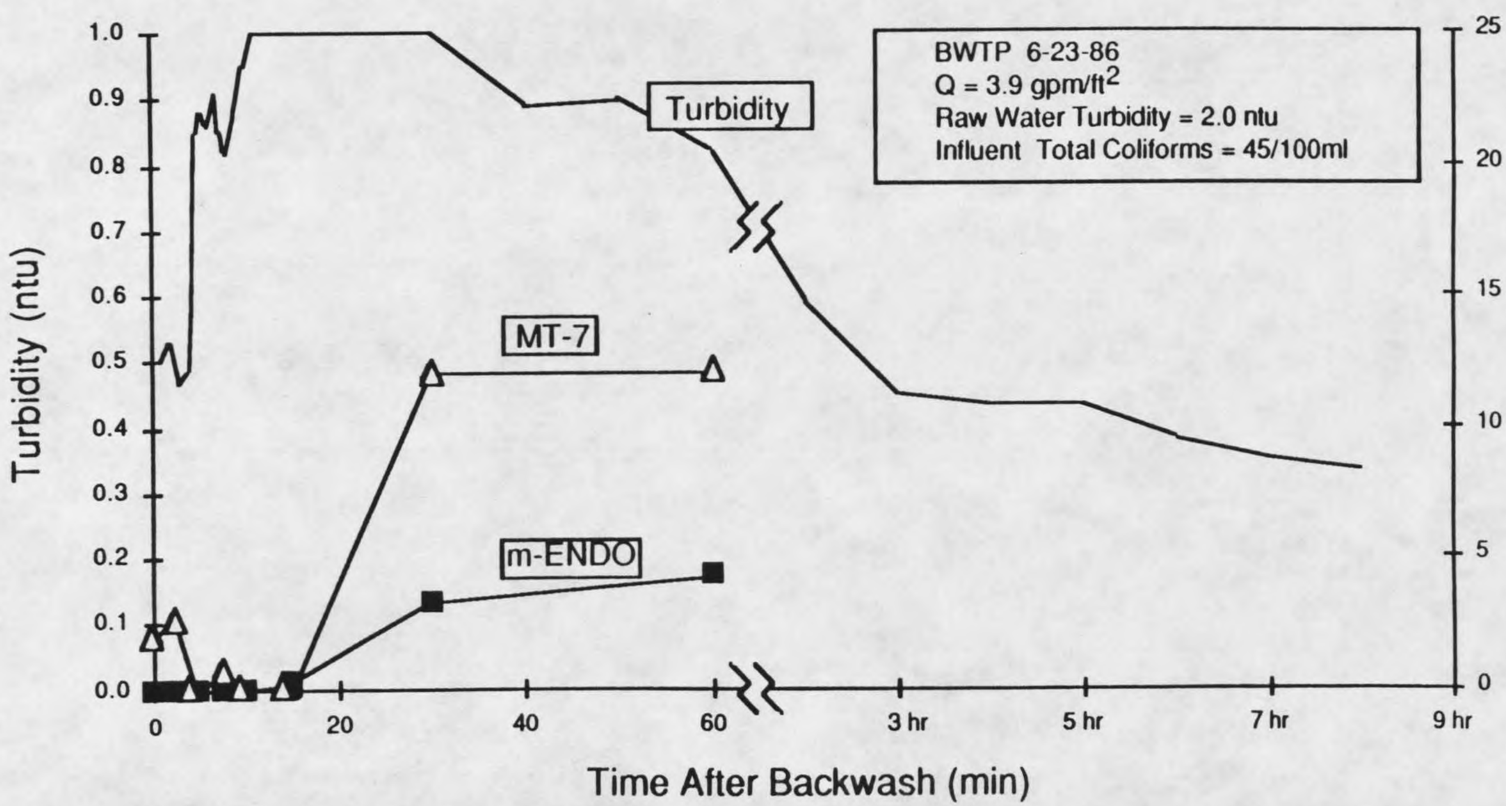

Figure 41. Total and Injured Coliform Levels During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 10.7 min.

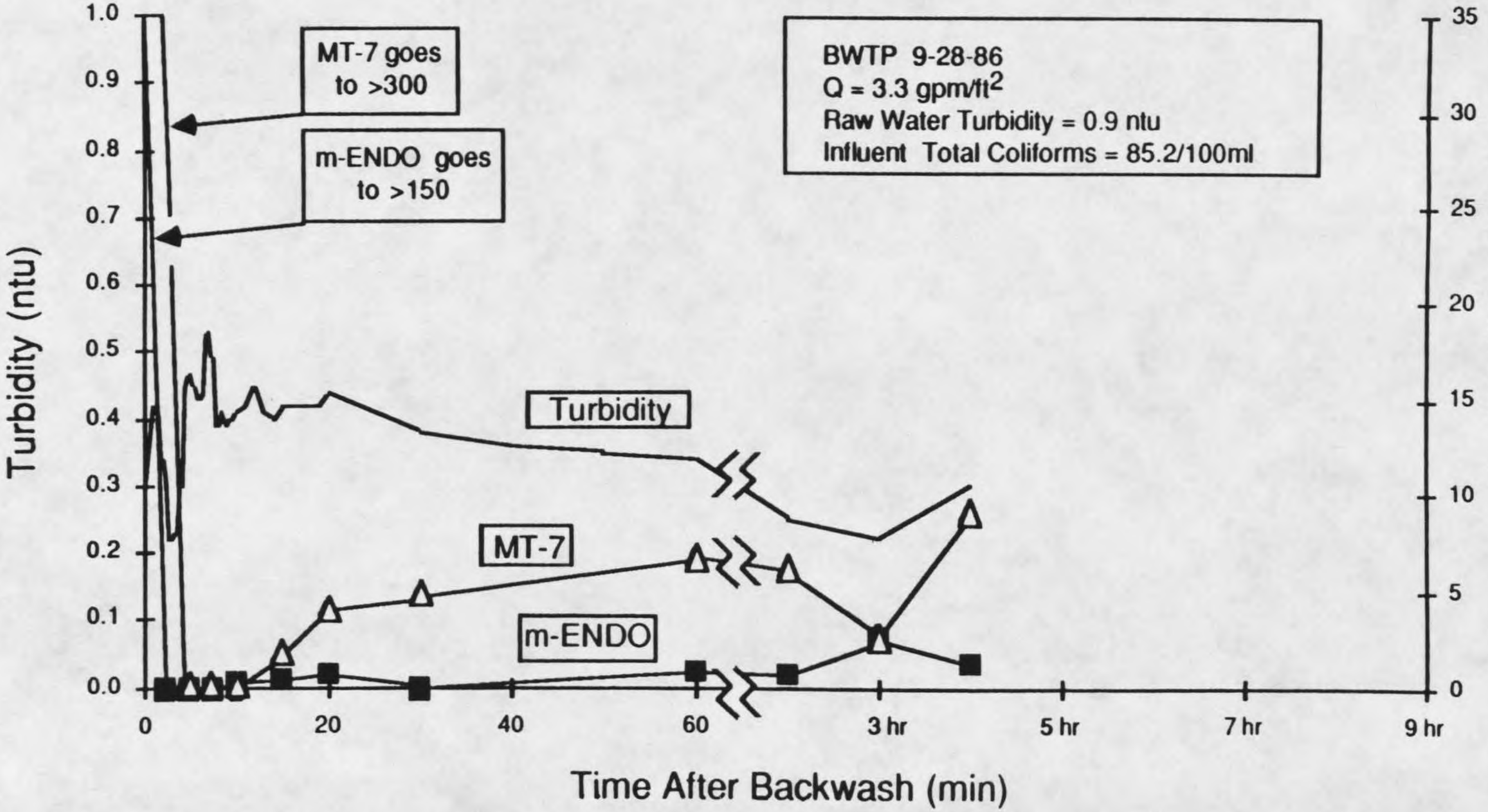

Figure 42. Total and Injured Coliform Levels During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 8.9 min.

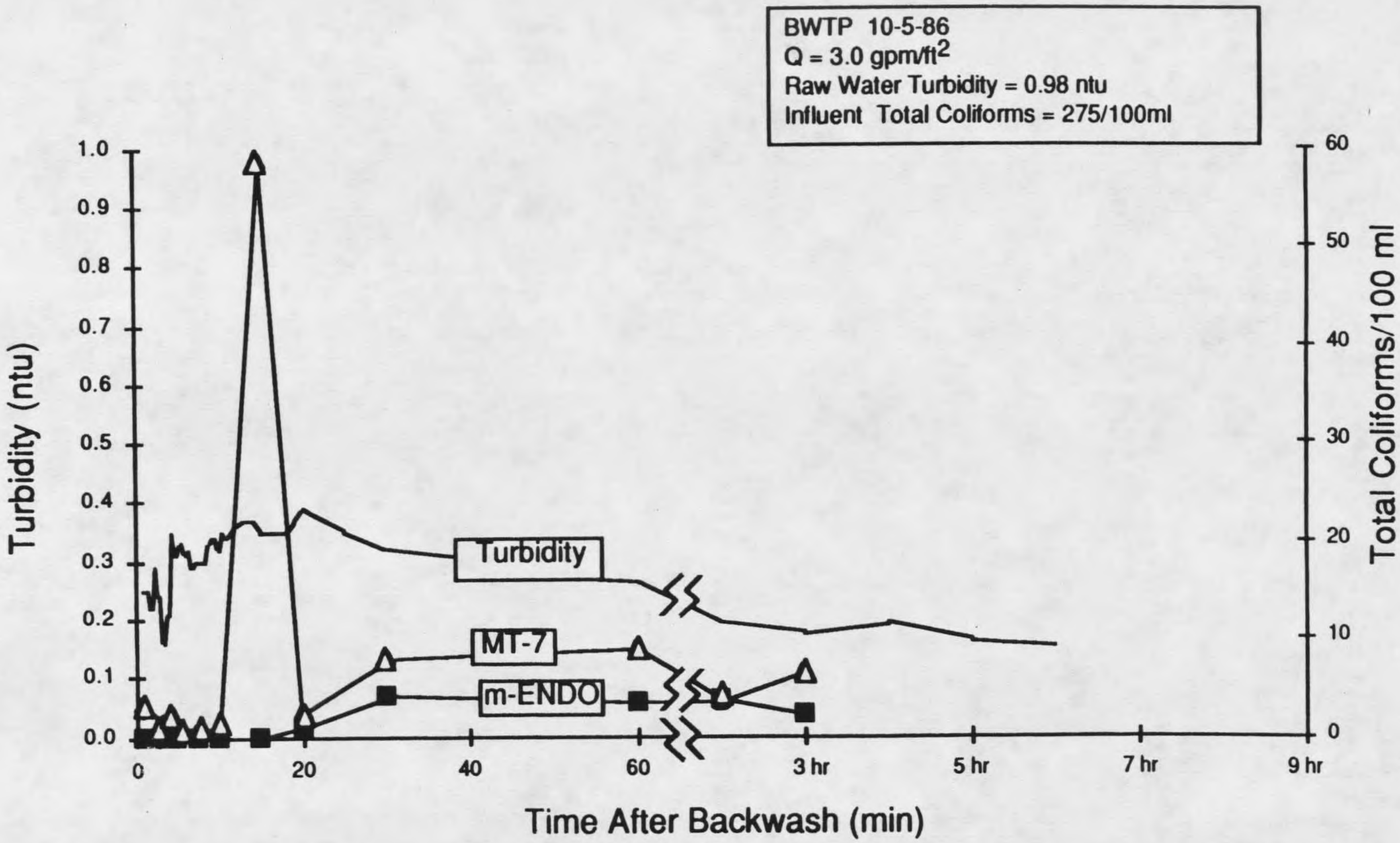

Figure 43. Total and Injured Coliform Levels During Initial Filtration. Bozeman Water Treatment Plant. Filter detention time = 13.9 min.

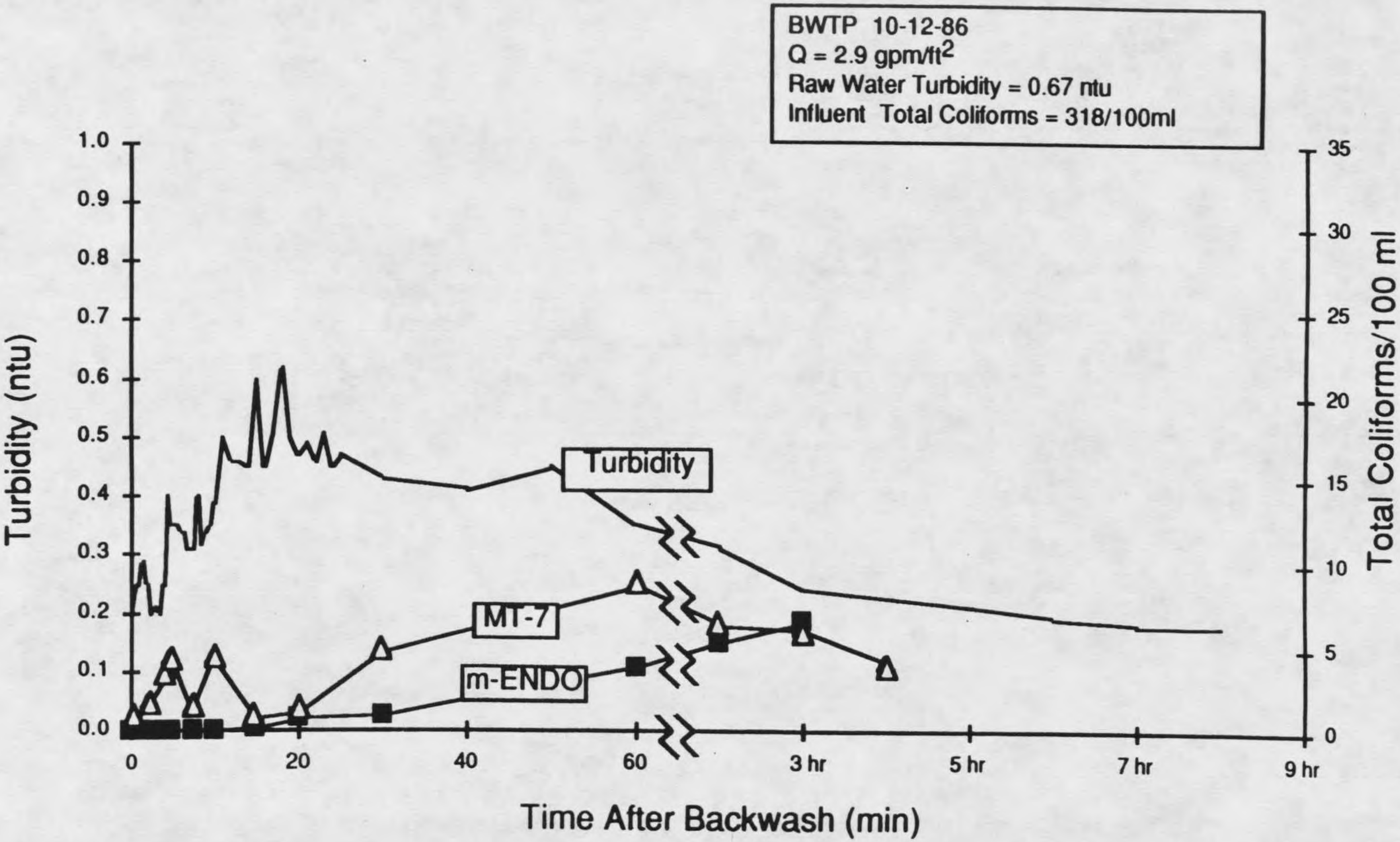

Figure 44. Total and Injured Coliform Levels During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 14.4 min.

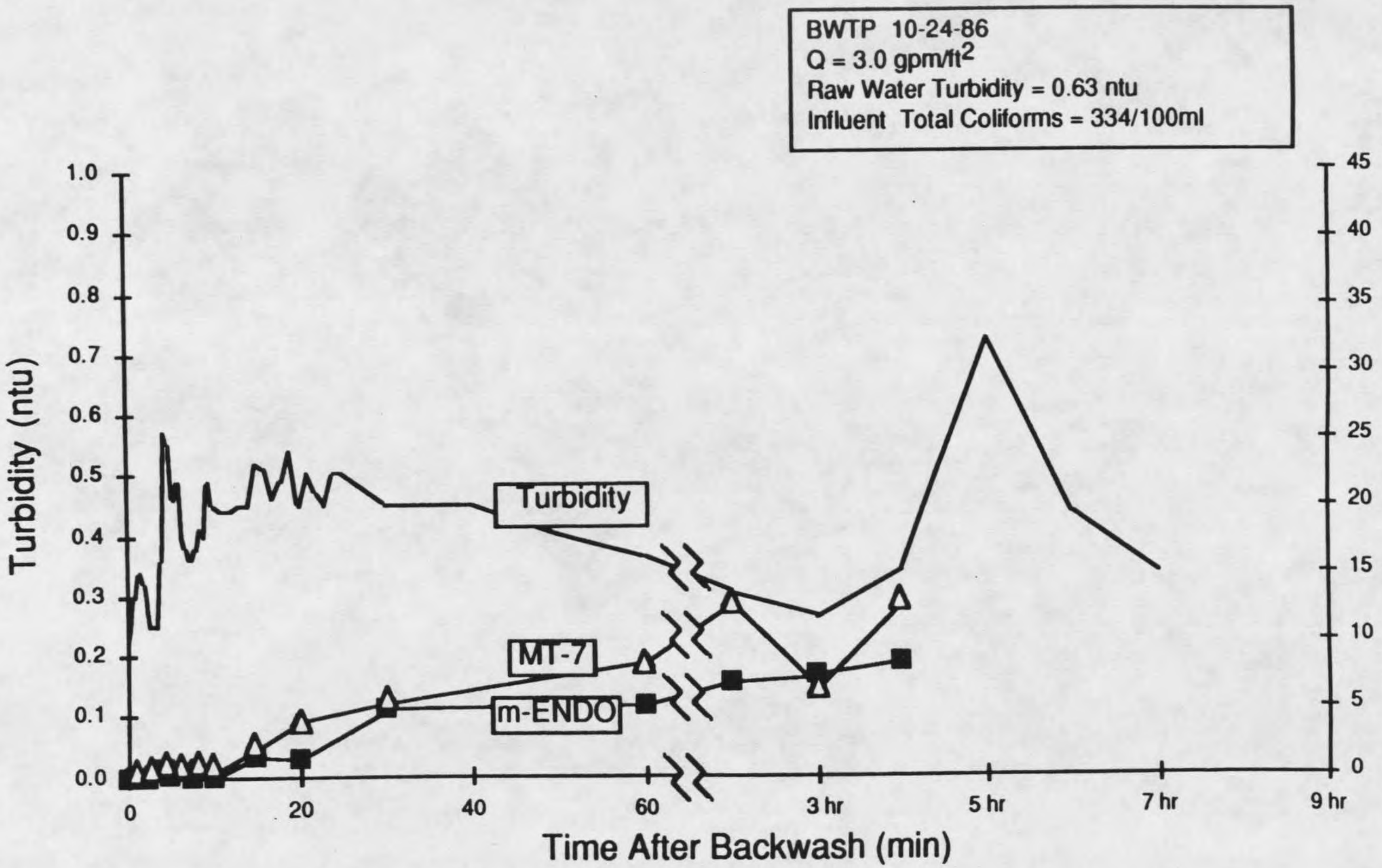

Figure 45. Total and Injured Coliform Levels During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 13.9 min.

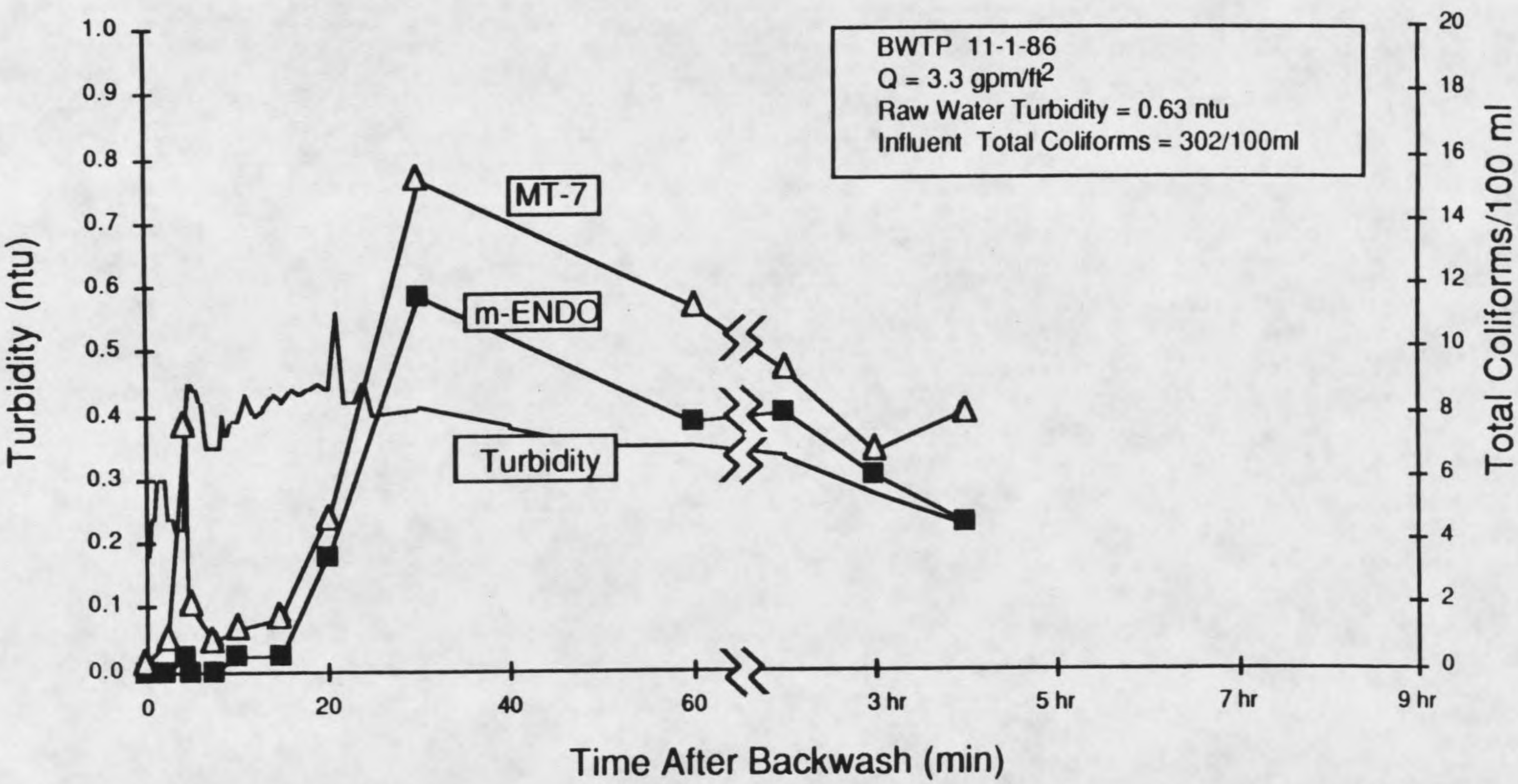

Figure 46. Total and Injured Coliform Levels During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 12.7 min.

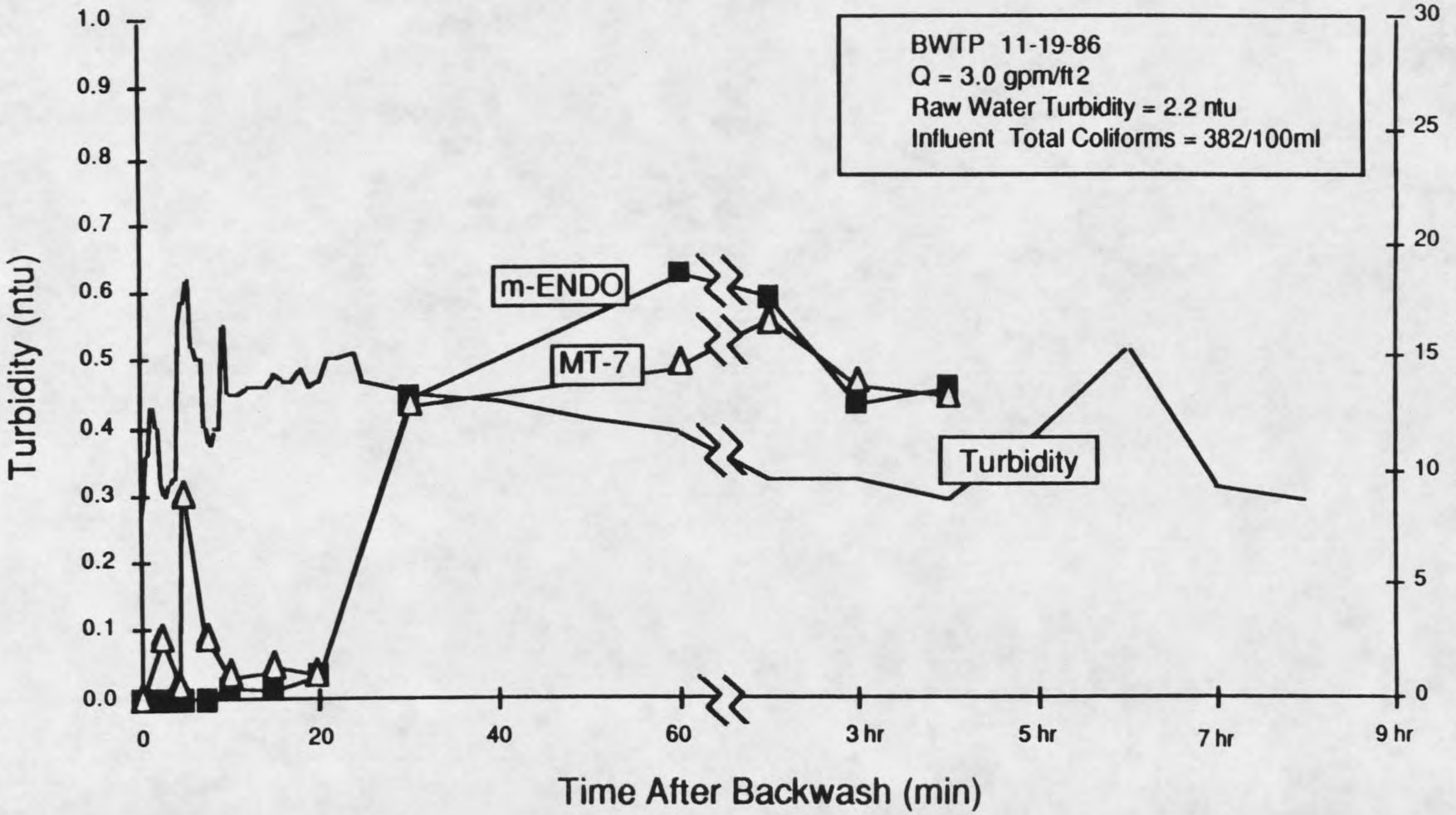

Figure 47. Total and Injured Coliform Levels During Initial Filtration. Bozeman Water Treatment Plant.
Filter detention time = 13.9 min.

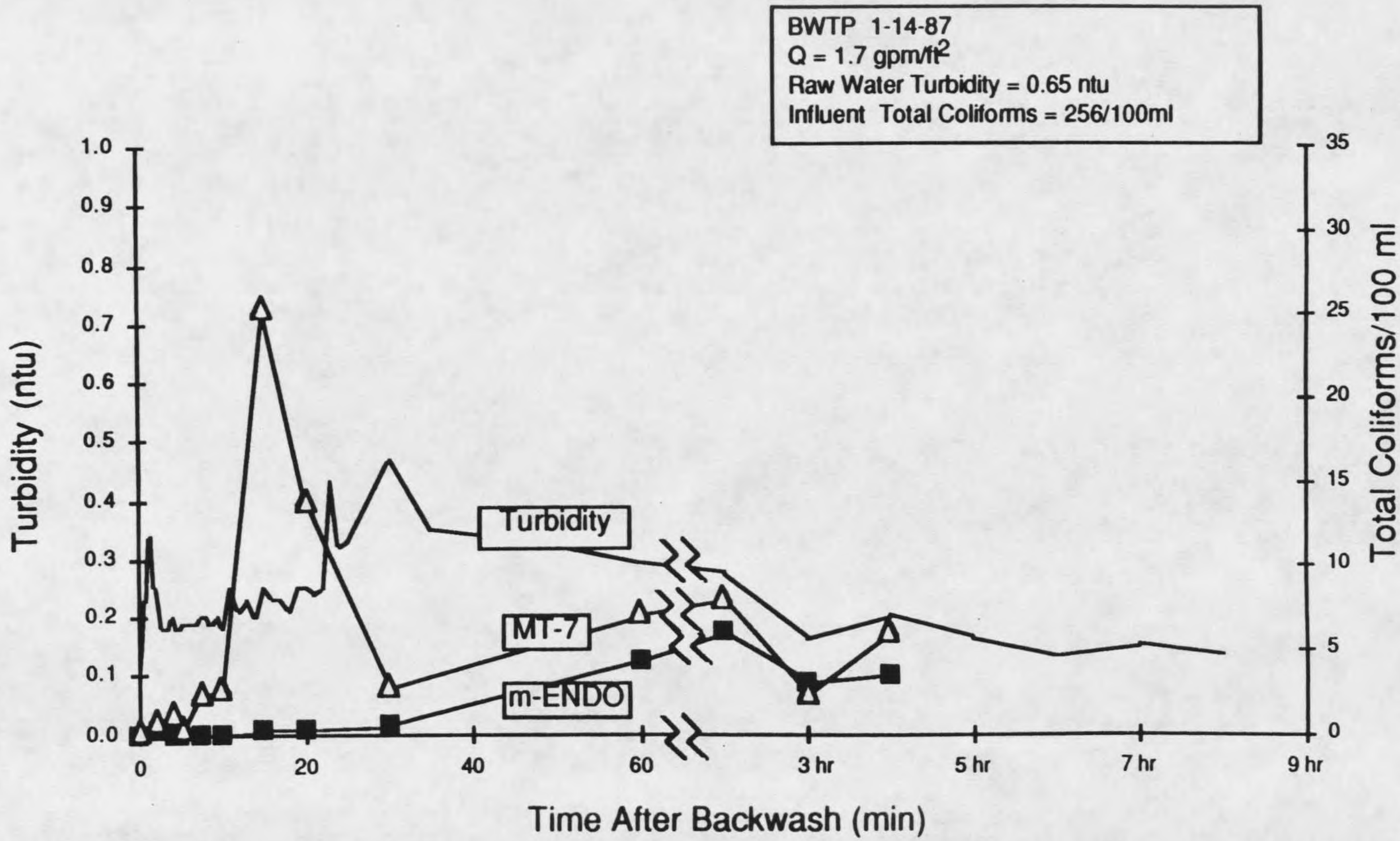

Figure 48. Total and Injured Coliform Levels During Initial Filtration. Bozeman Water Treatment Plant. Filter detention time = 24.6 min.

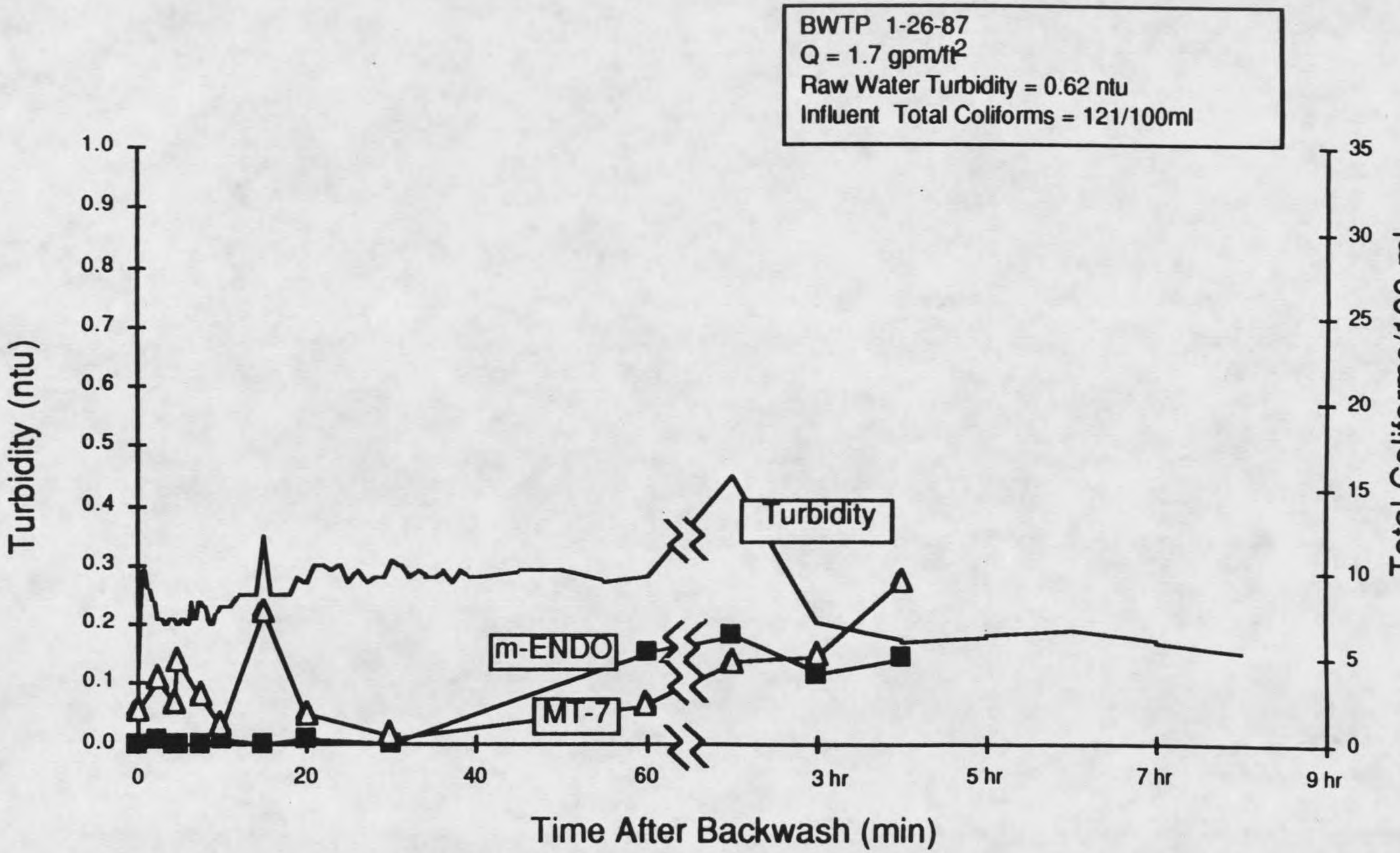

Figure 49. Total and Injured Coliform Levels During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 24.6 min.

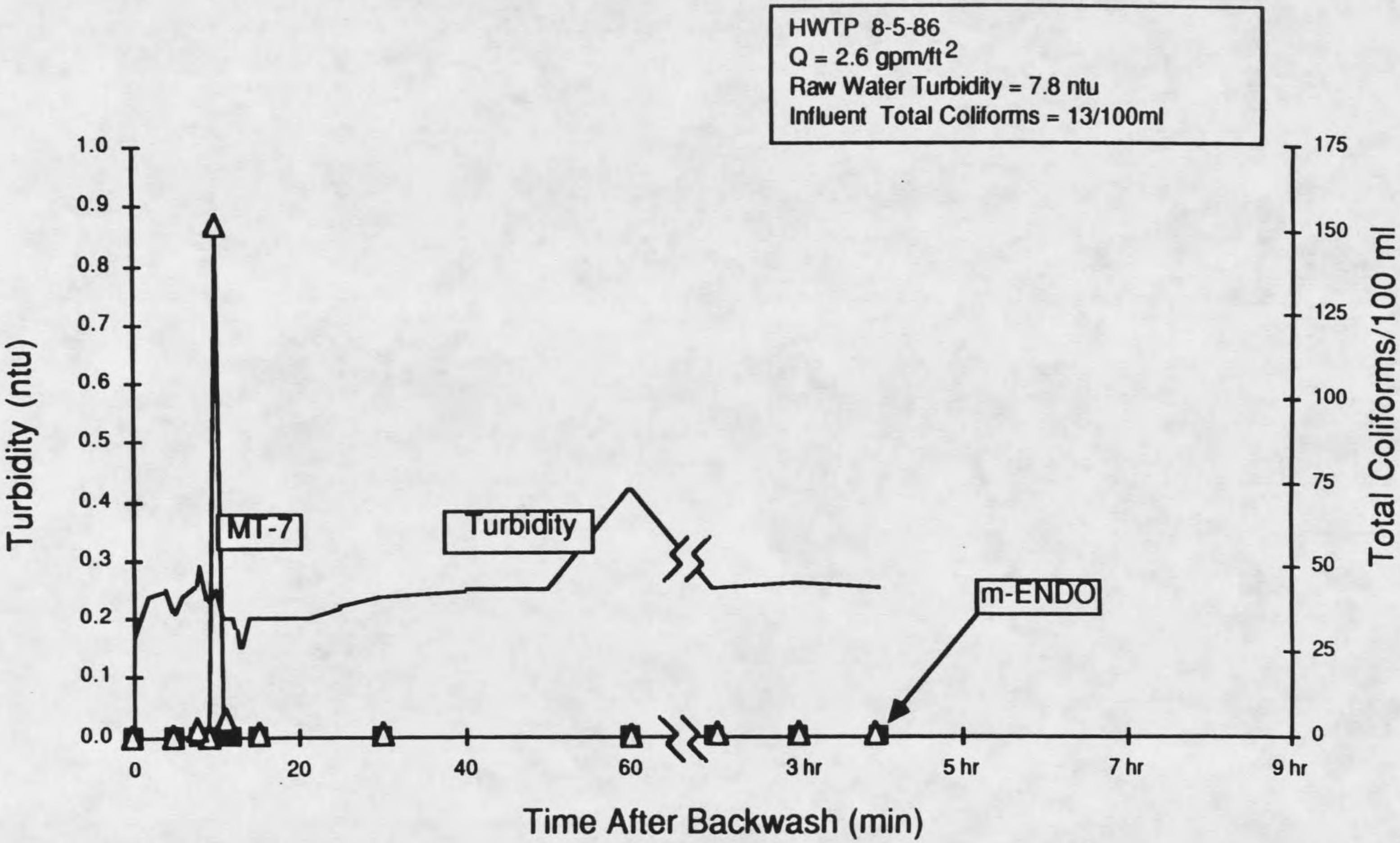

Figure 50. Total and Injured Coliform Levels During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

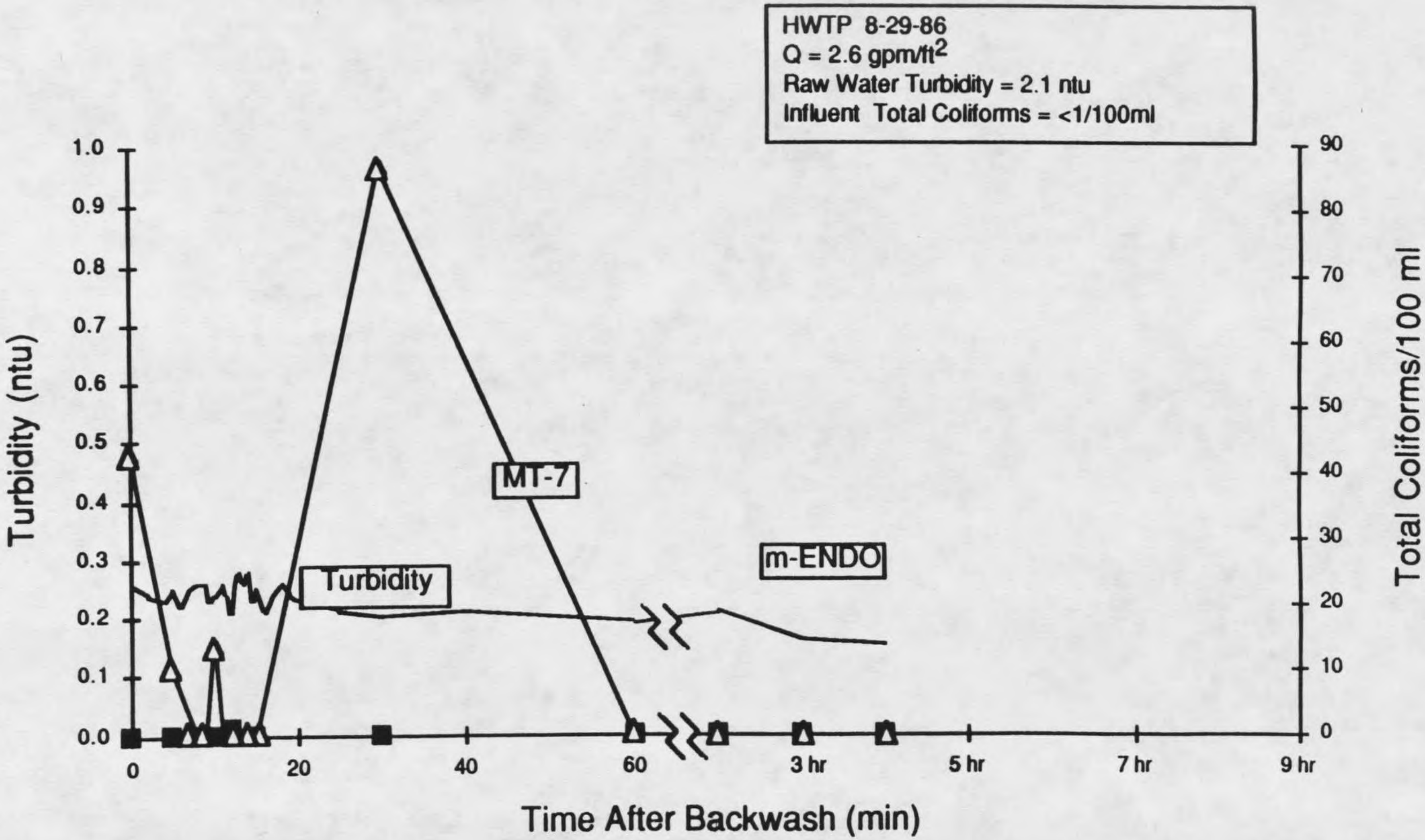

Figure 51. Total and Injured Coliform Levels During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

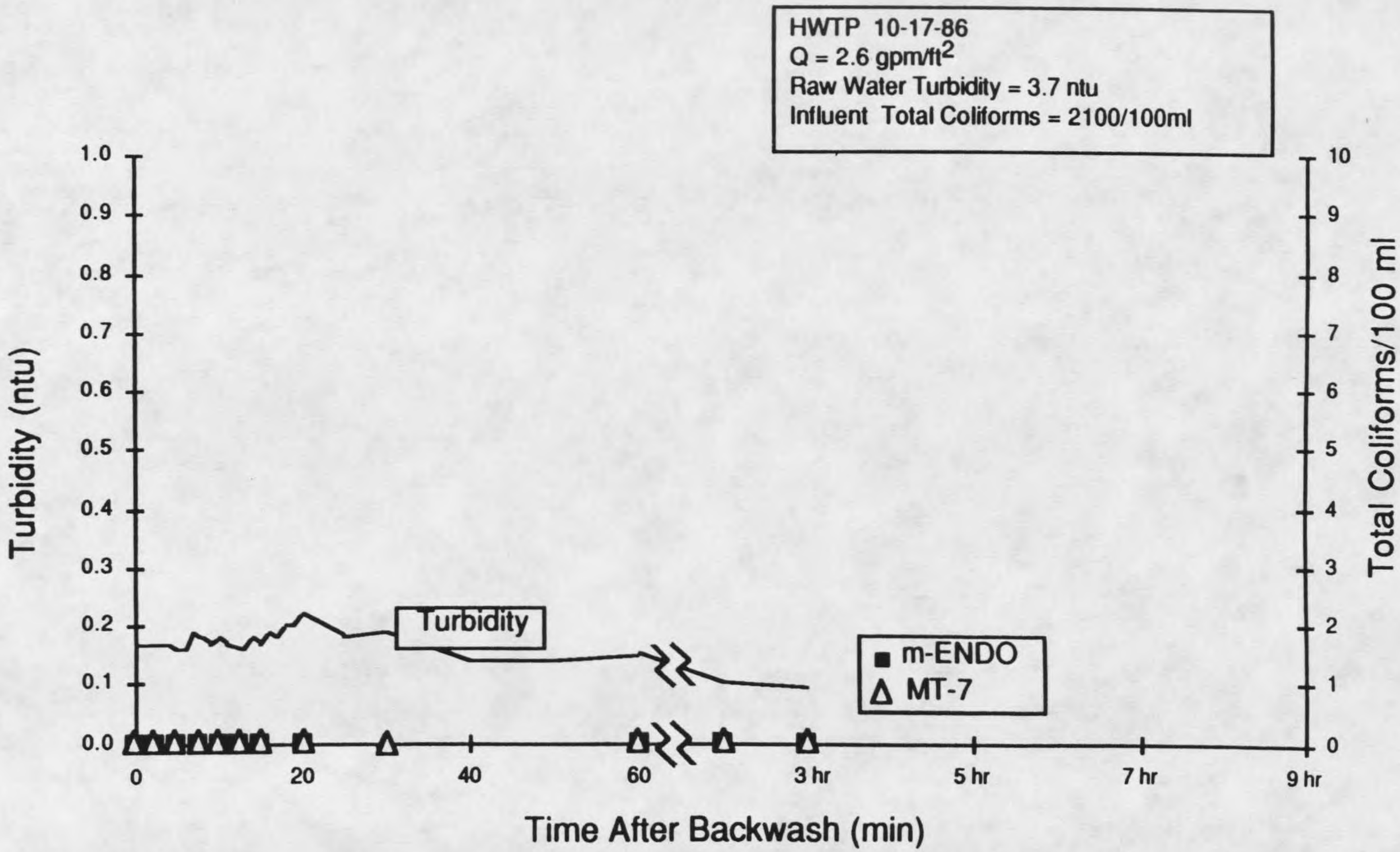

Figure 52. Total and Injured Coliform Levels During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

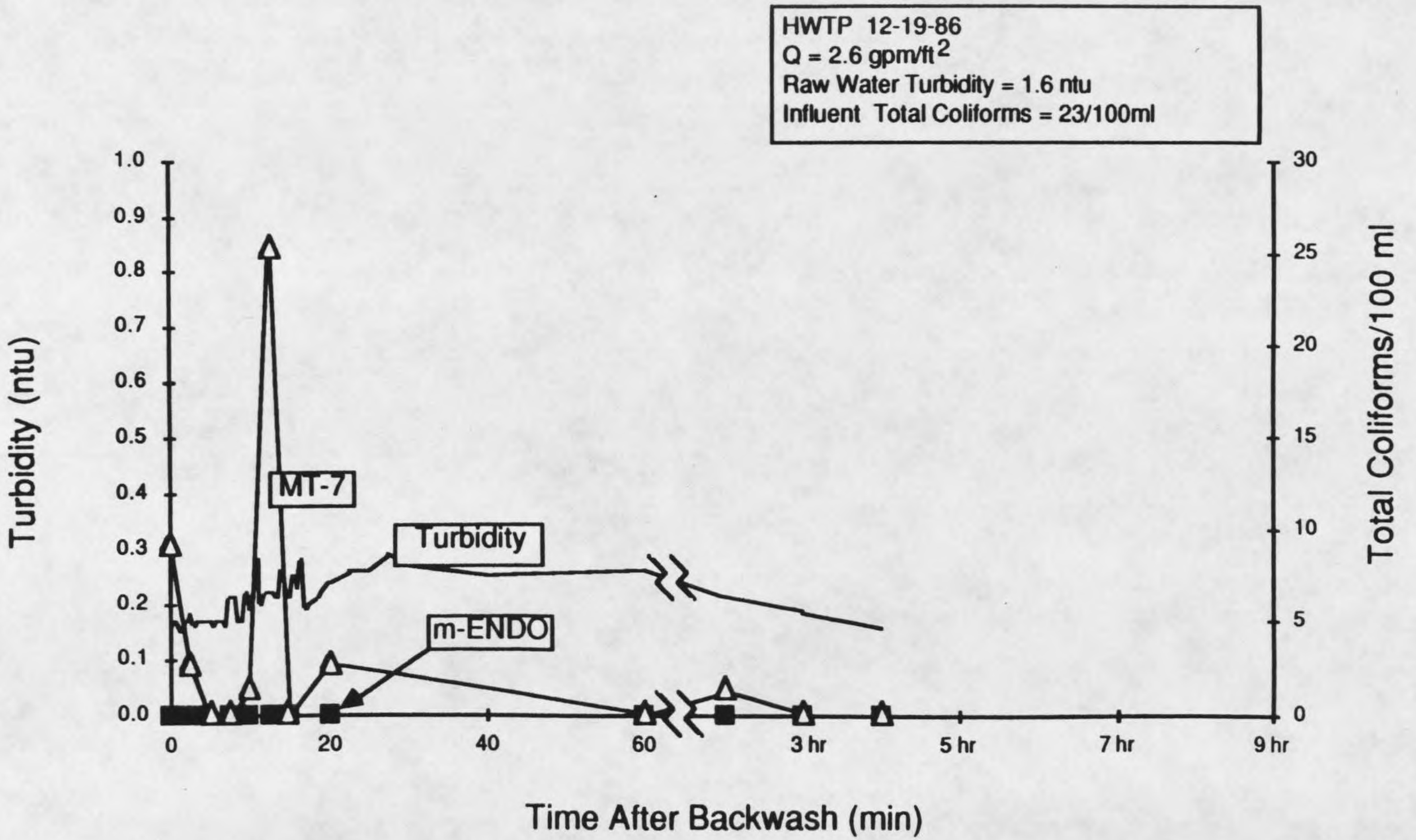

Figure 53. Total and Injured Coliform Levels During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

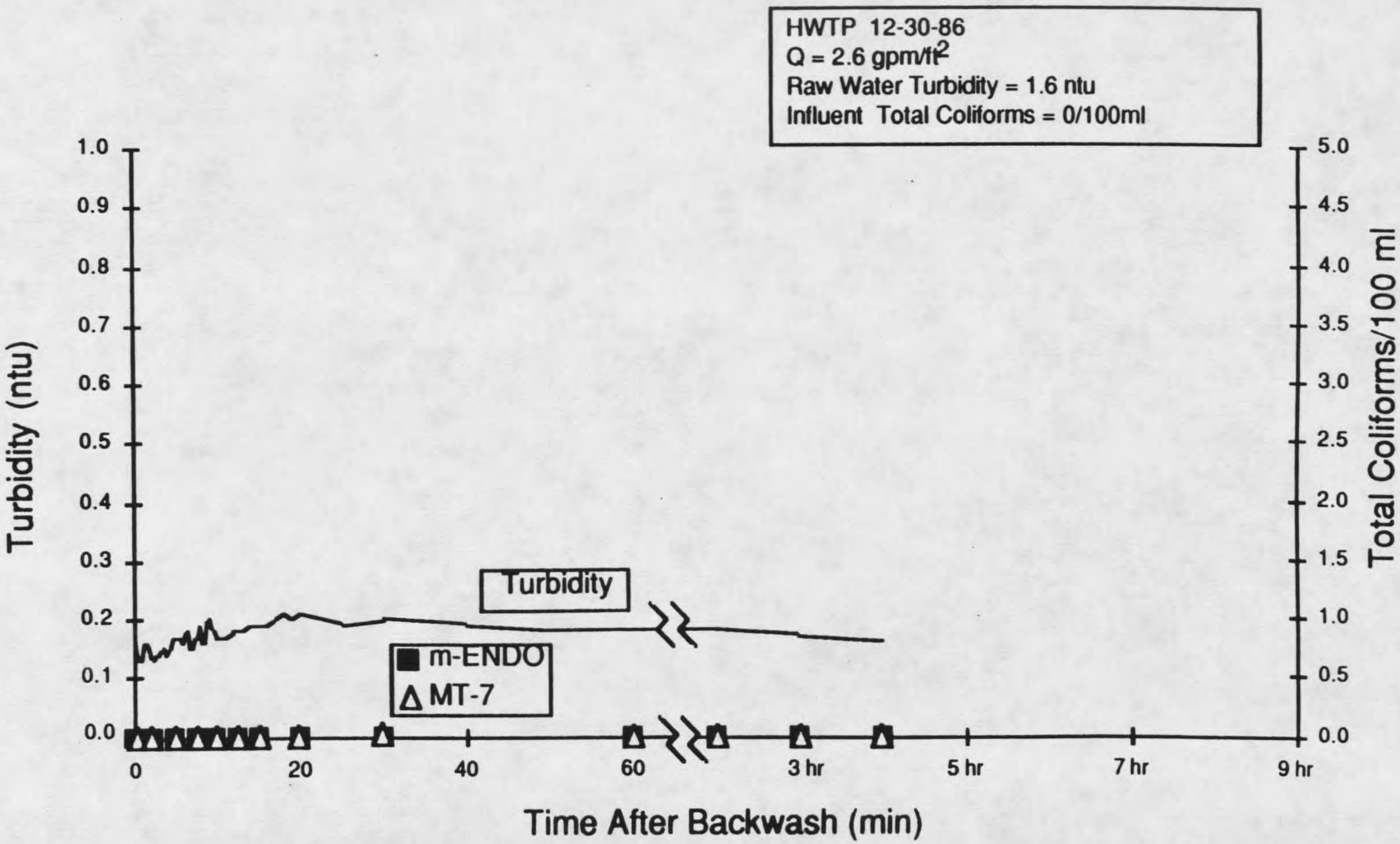

Figure 54. Total and Injured Coliform Levels During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

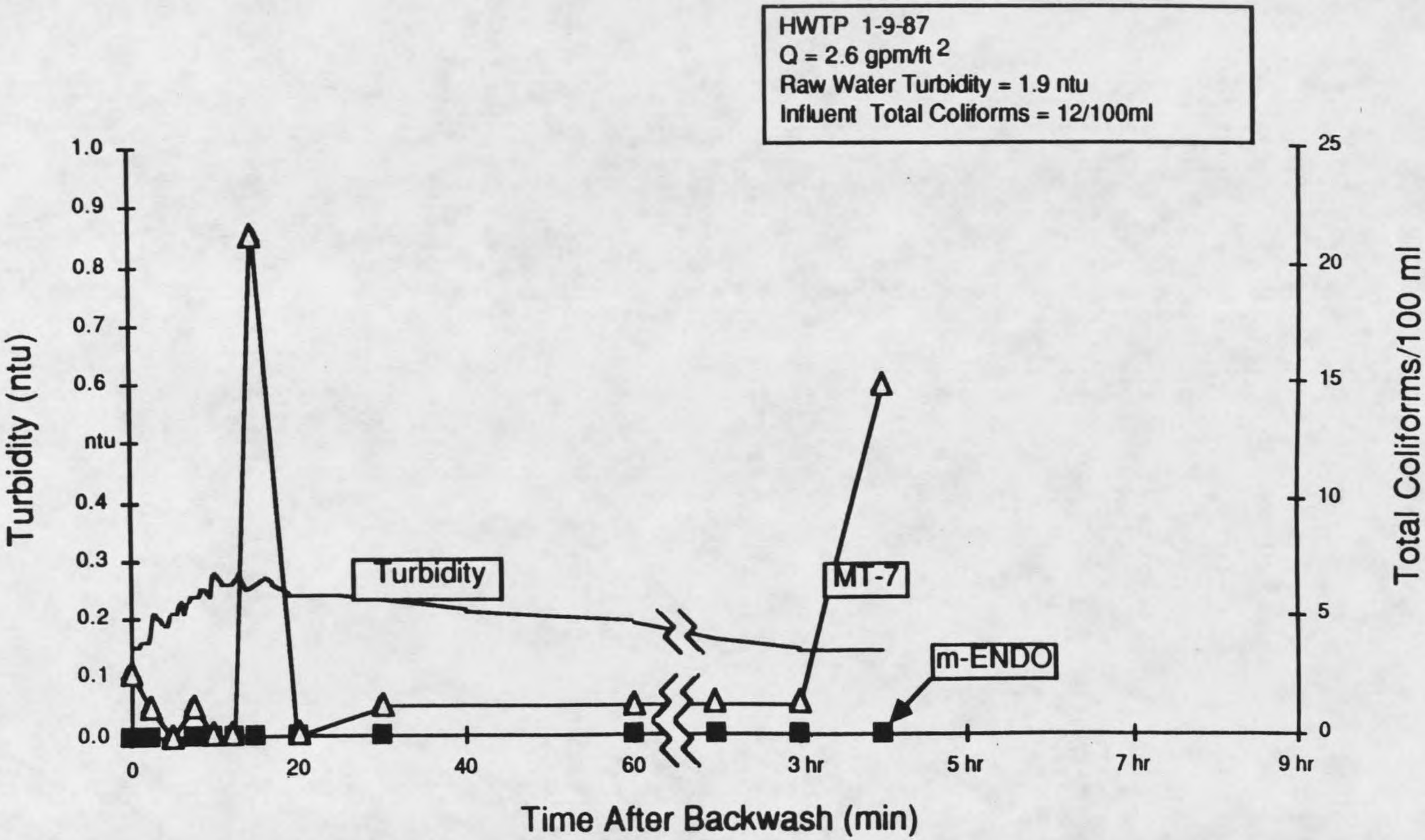

Figure 55. Total and Injured Coliform Levels During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

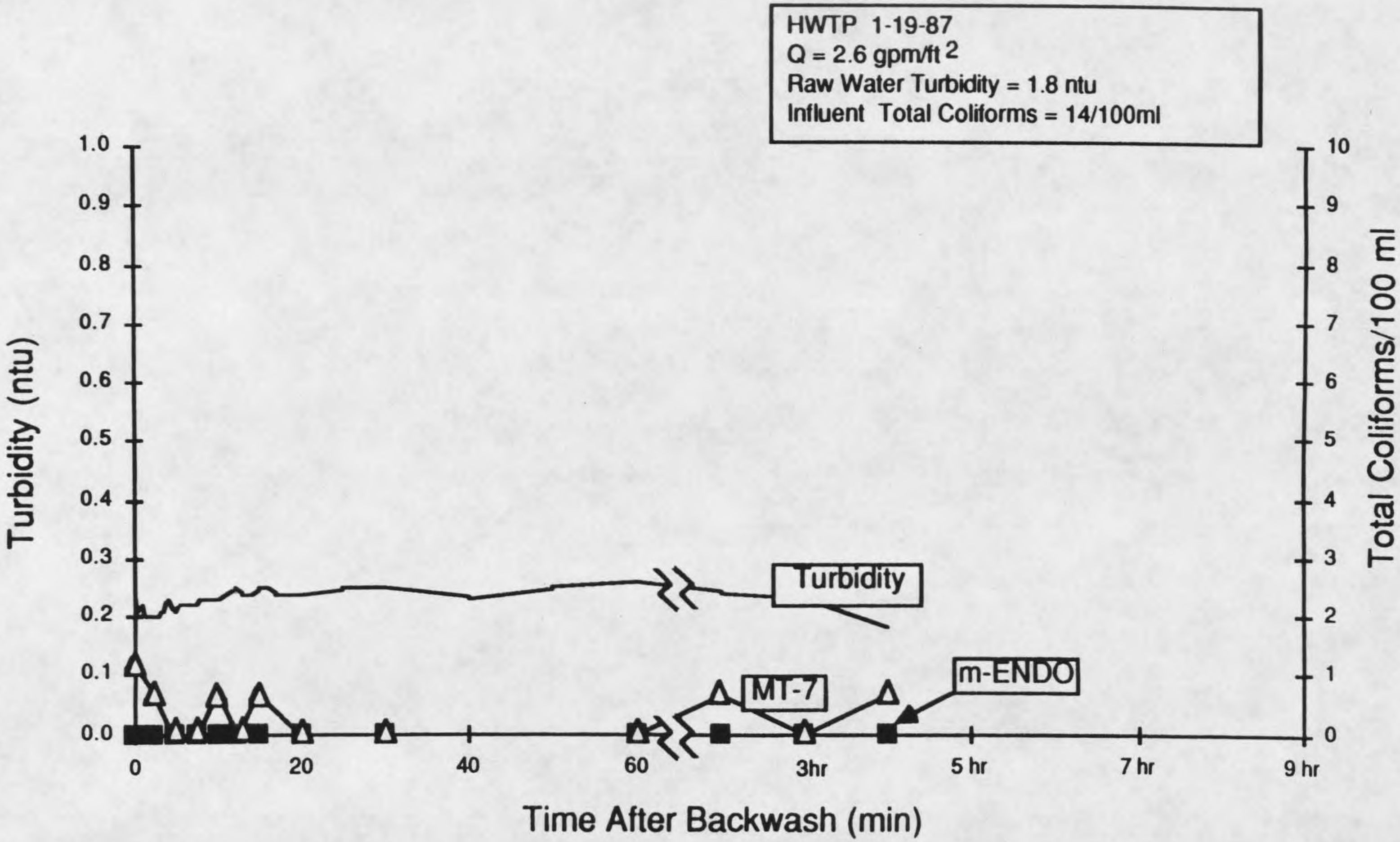

Figure 56. Total and Injured Coliform Levels During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

APPENDIX II
ADDITIONAL FILTER RUNS WITH HETEROTROPHIC PLATE COUNTS (HPC)

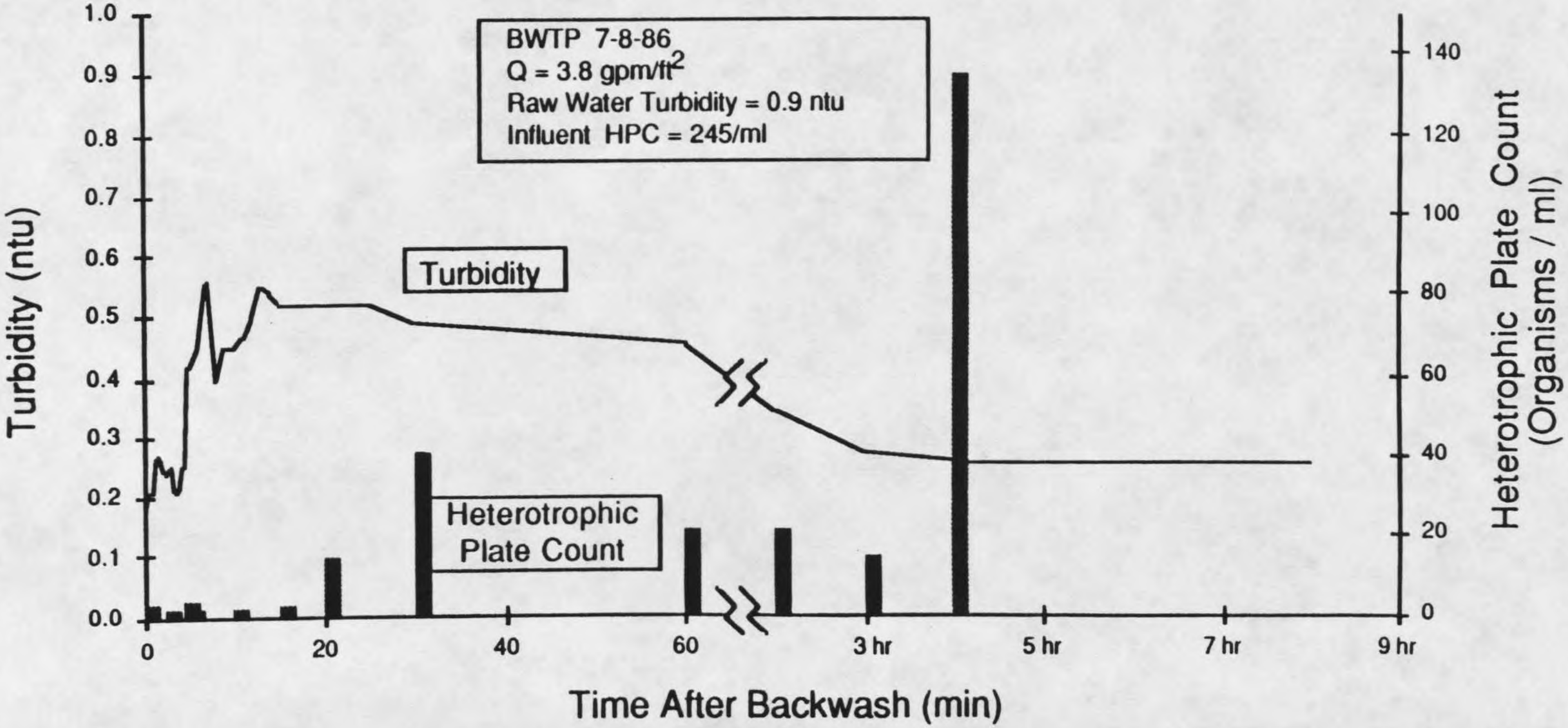

Figure 57. Heterotrophic Plate Counts During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 11.0 min.

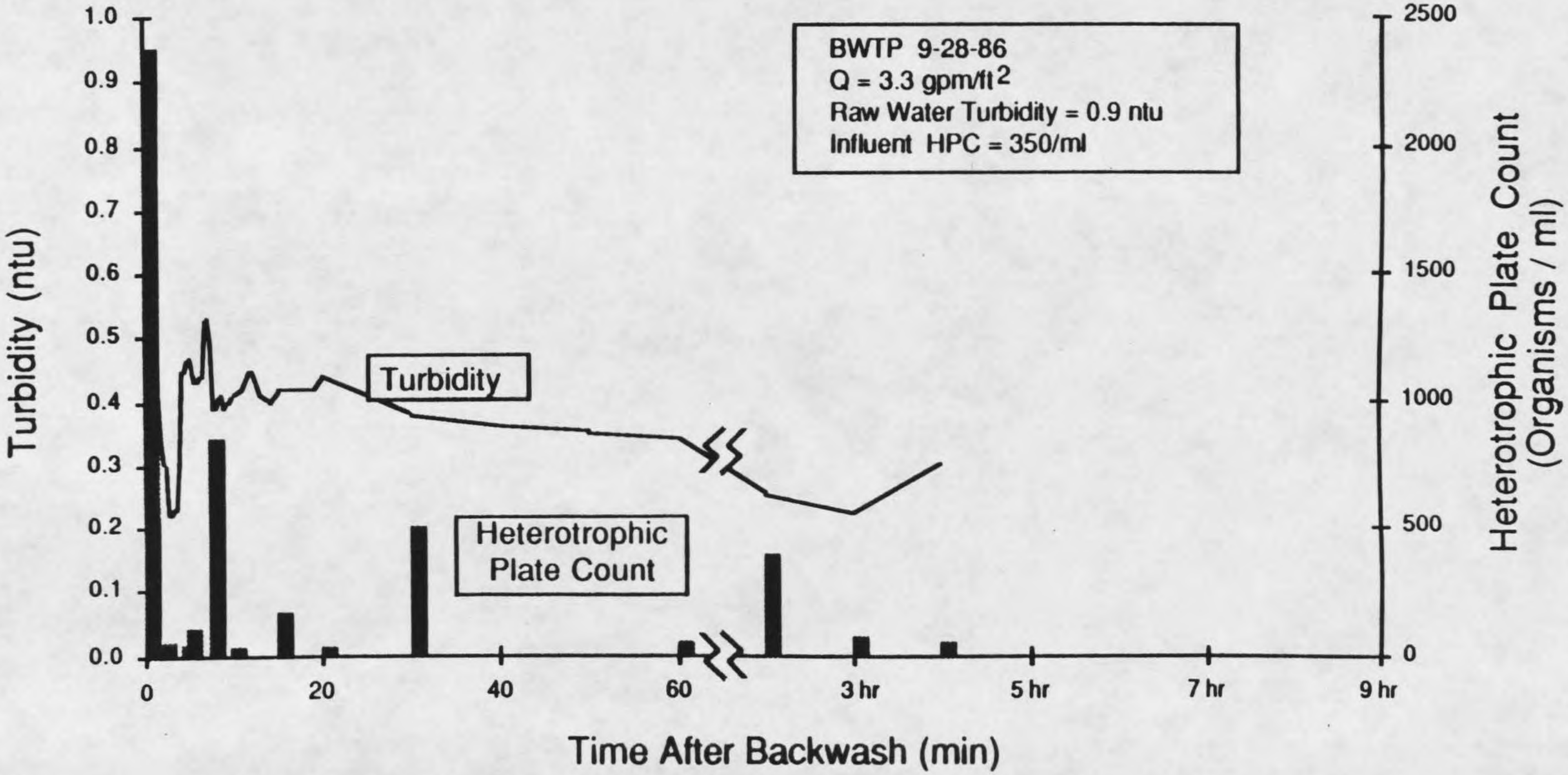

Figure 58. Heterotrophic Plate Counts During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 8.9 min.

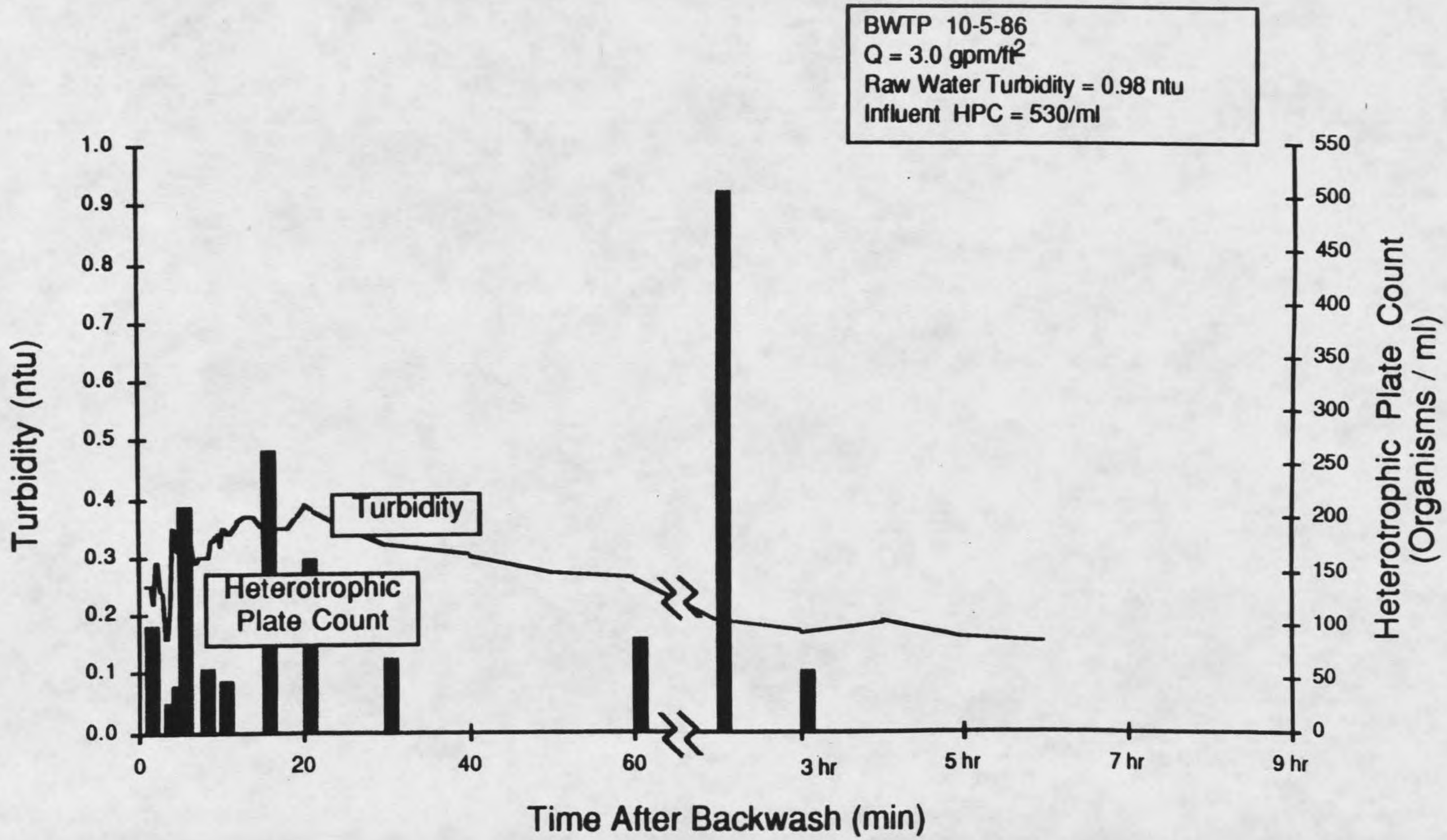

Figure 59. Heterotrophic Plate Counts During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 13.9 min.

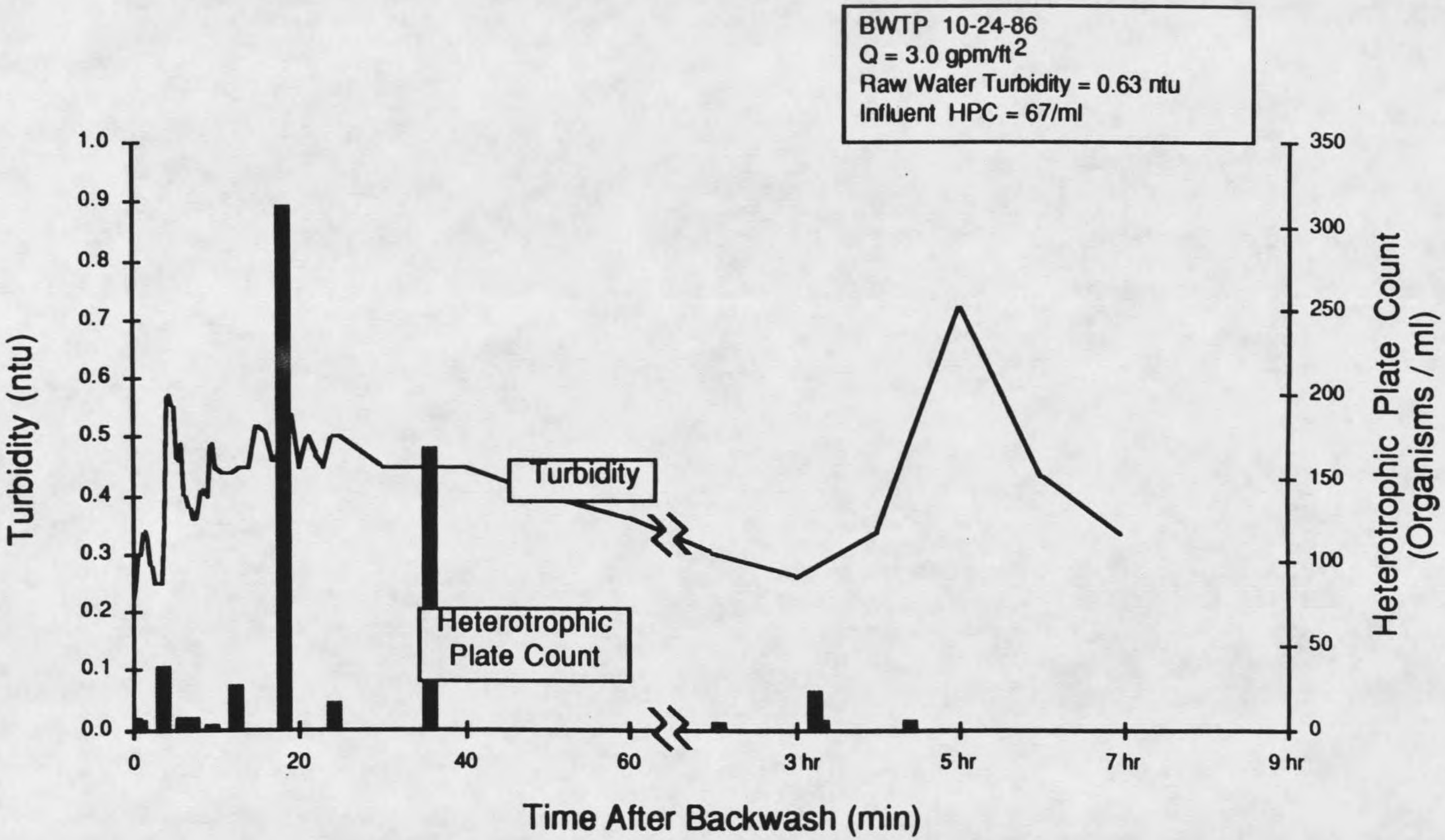

Figure 60. Heterotrophic Plate Counts During Initial Filtration. Bozeman Water Treatment Plant. Filter detention time = 13.9 min.

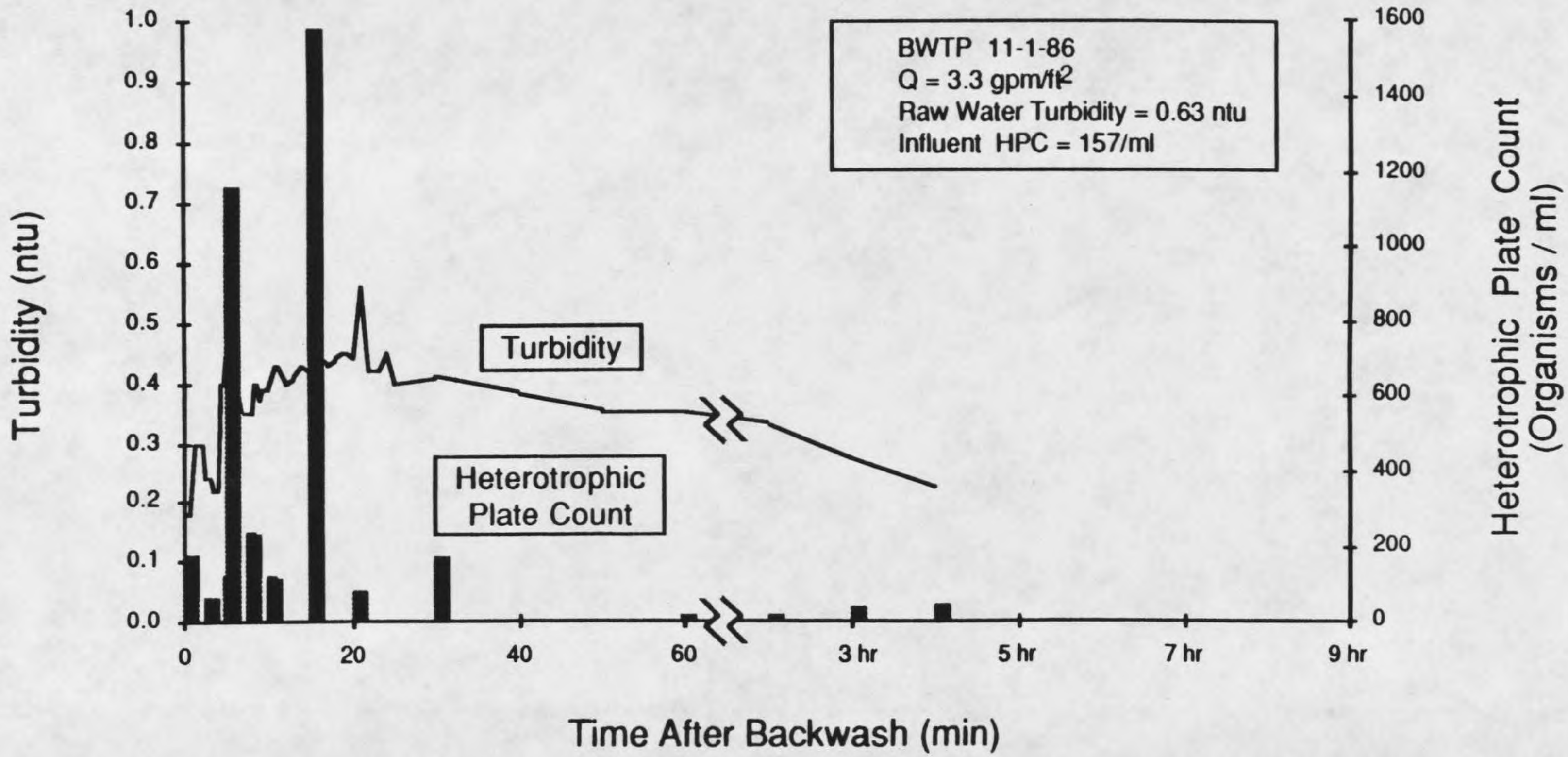

Figure 61. Heterotrophic Plate Counts During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 12.7 min.

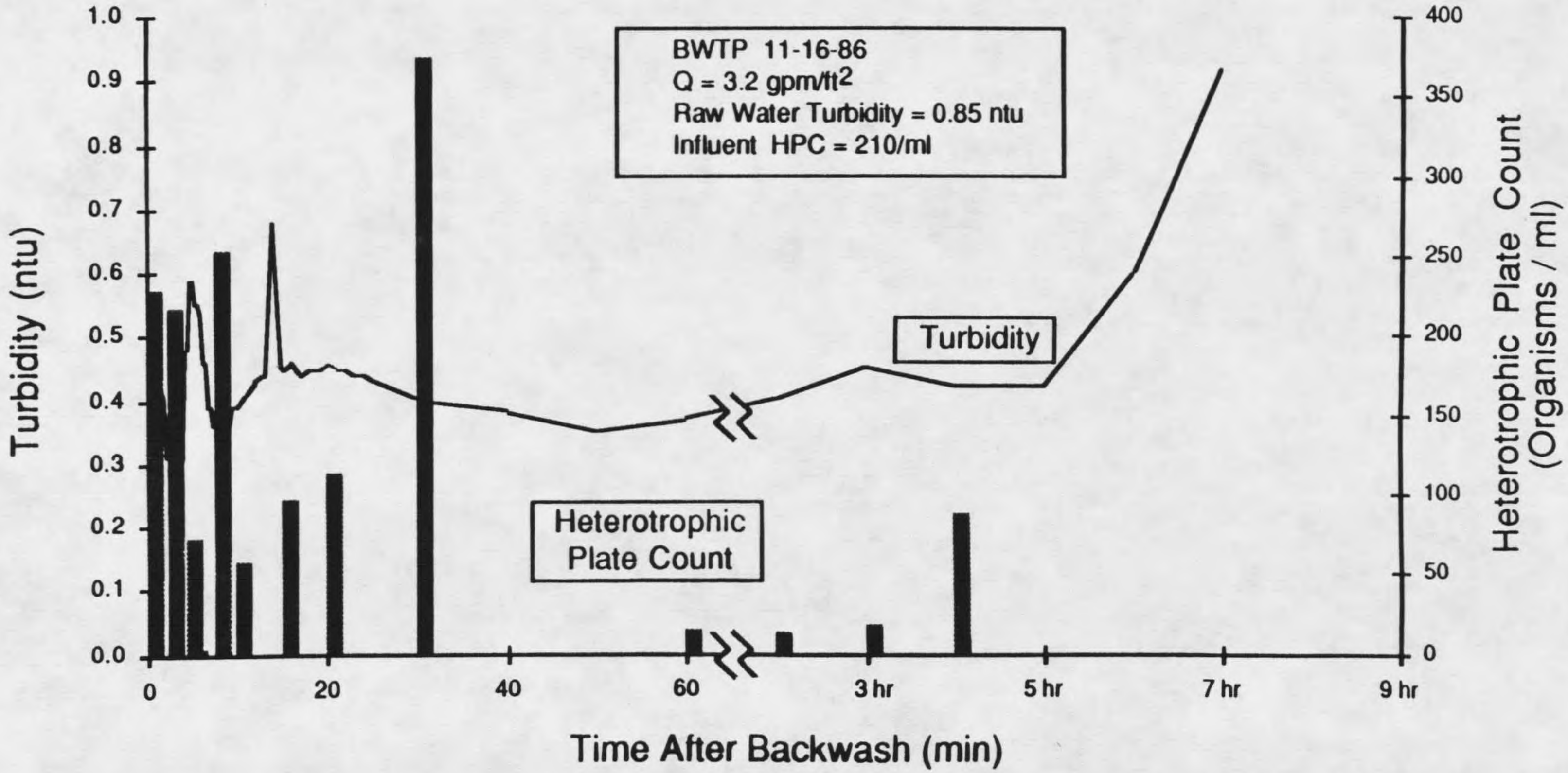

Figure 62. Heterotrophic Plate Counts During Initial Filtration. Bozeman Water Treatment Plant. Filter detention time = 13.1 min.

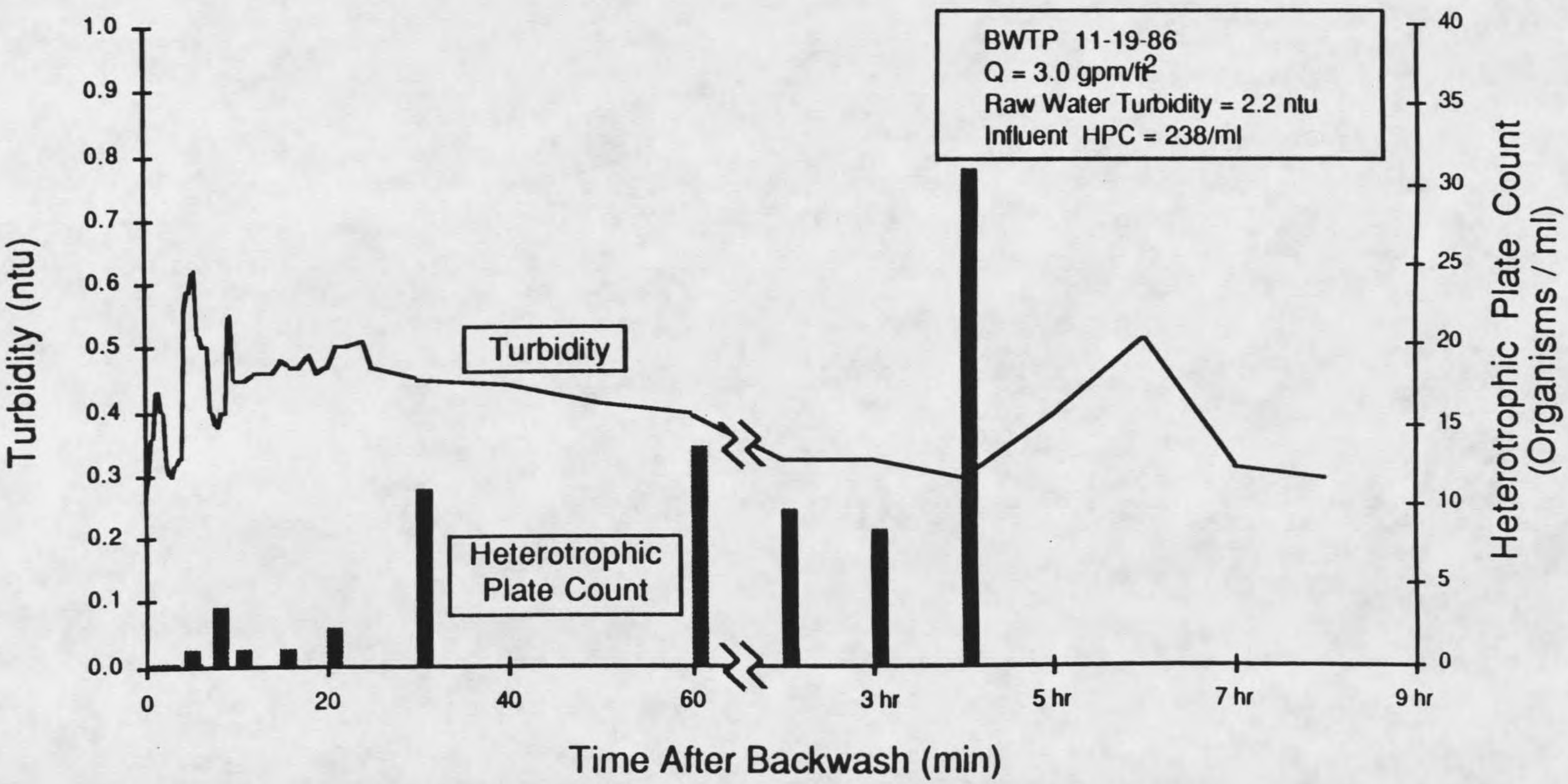

Figure 63. Heterotrophic Plate Counts During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 13.9 min.

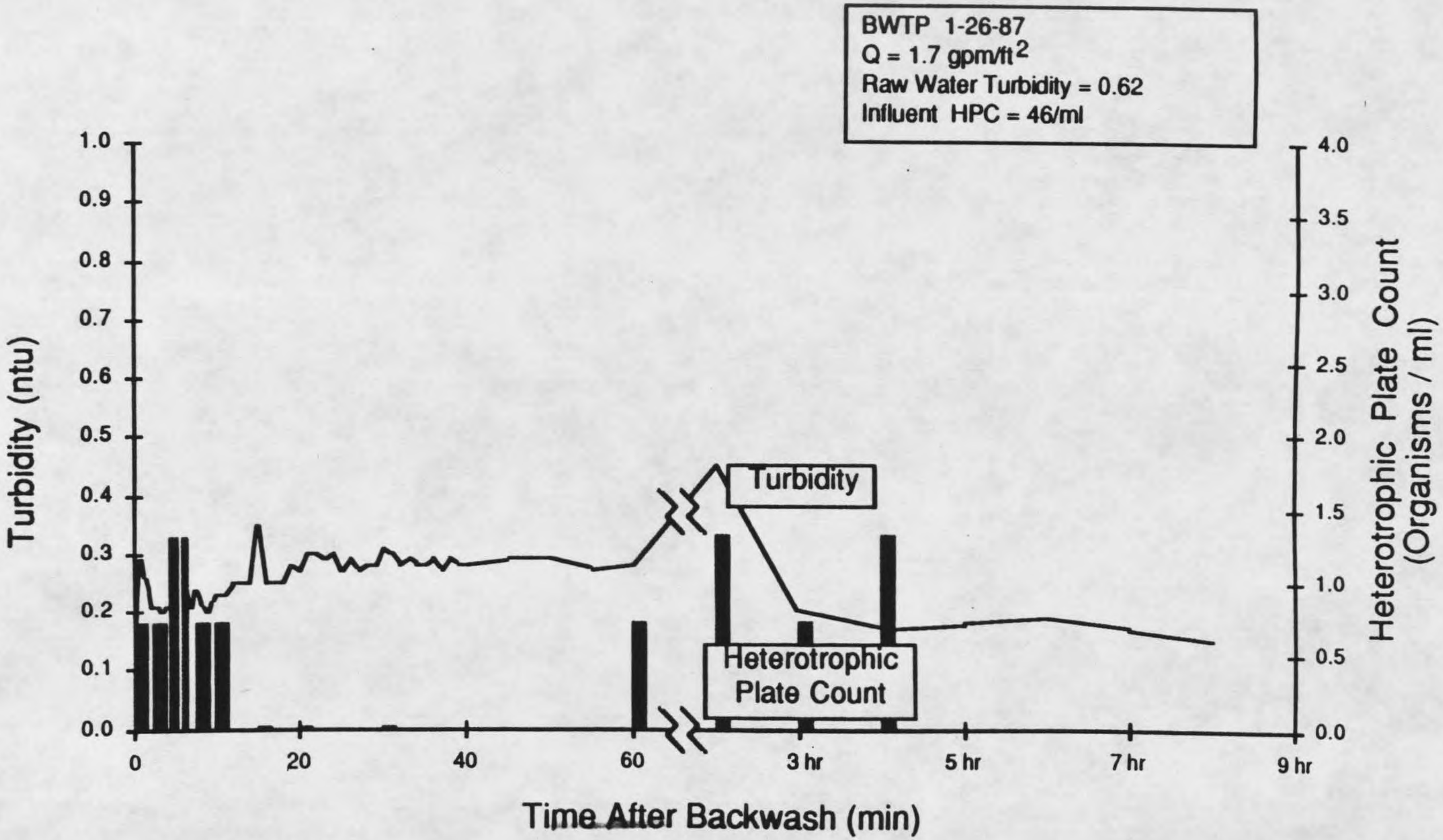

Figure 64. Heterotrophic Plate Counts During Initial Filtration.
Bozeman Water Treatment Plant.
Filter detention time = 24.6 min.

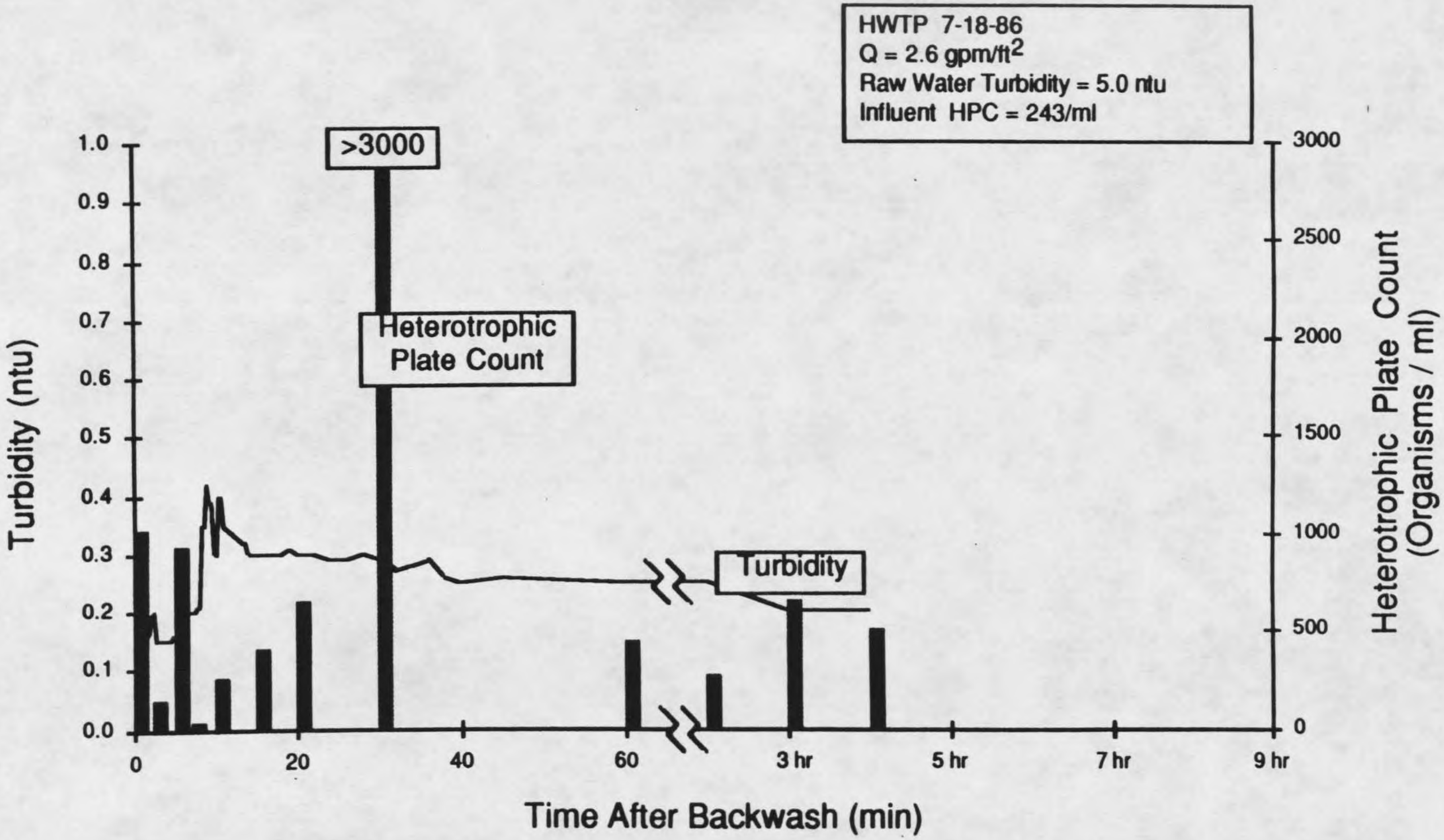

Figure 65. Heterotrophic Plate Counts During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

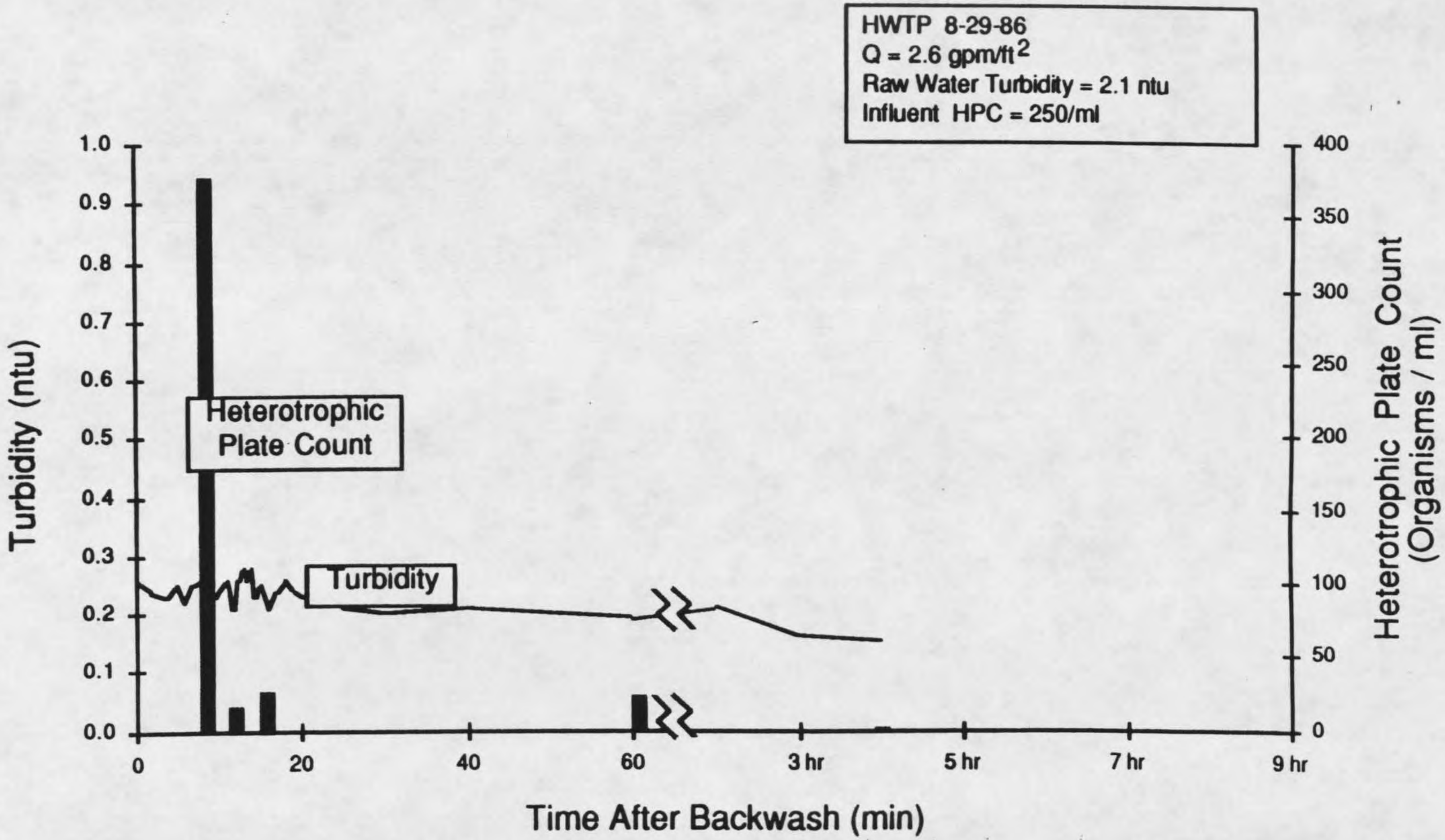

Figure 66. Heterotrophic Plate Counts During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

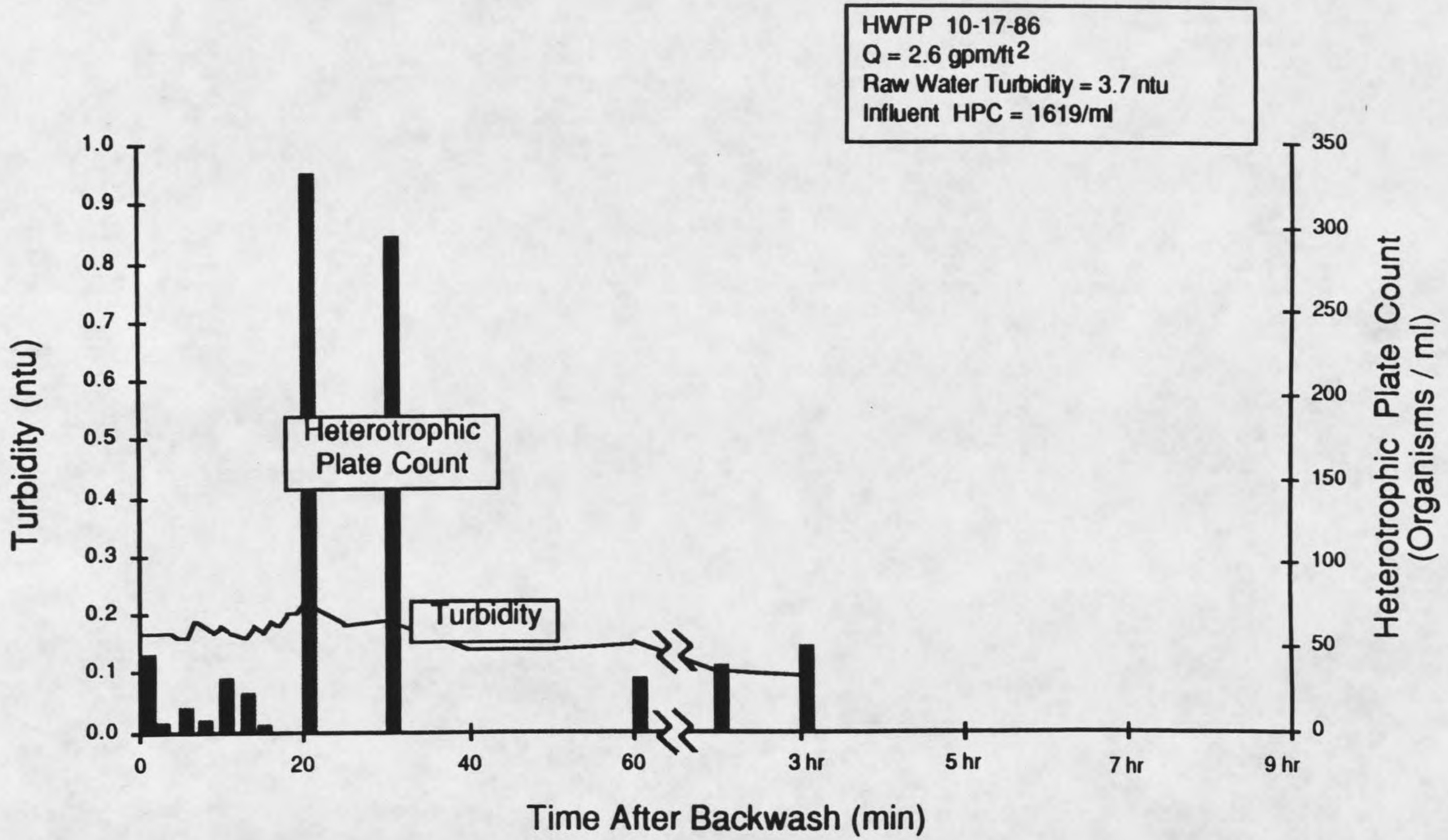

Figure 67. Heterotrophic Plate Counts During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

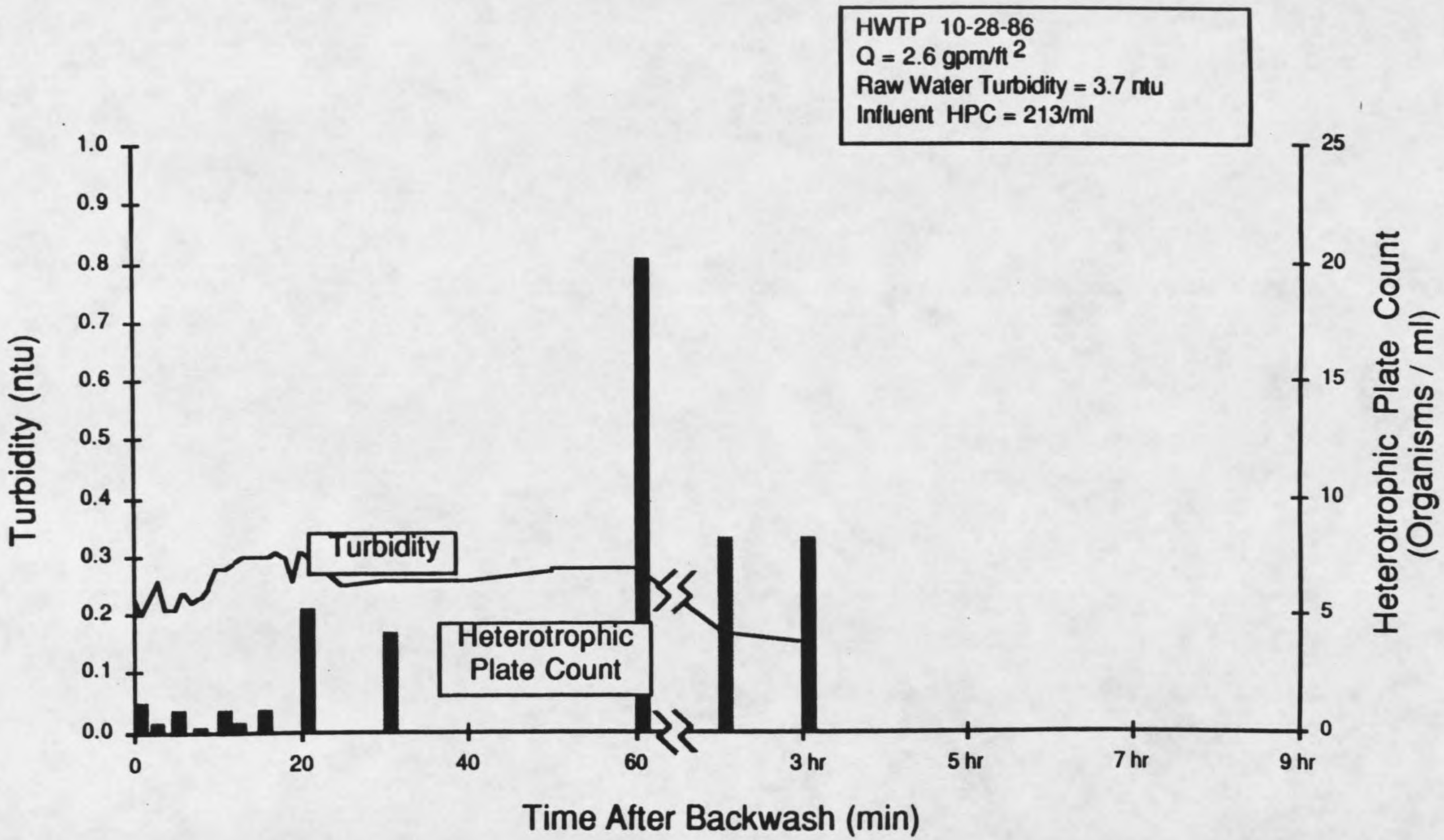

Figure 68. Heterotrophic Plate Counts During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

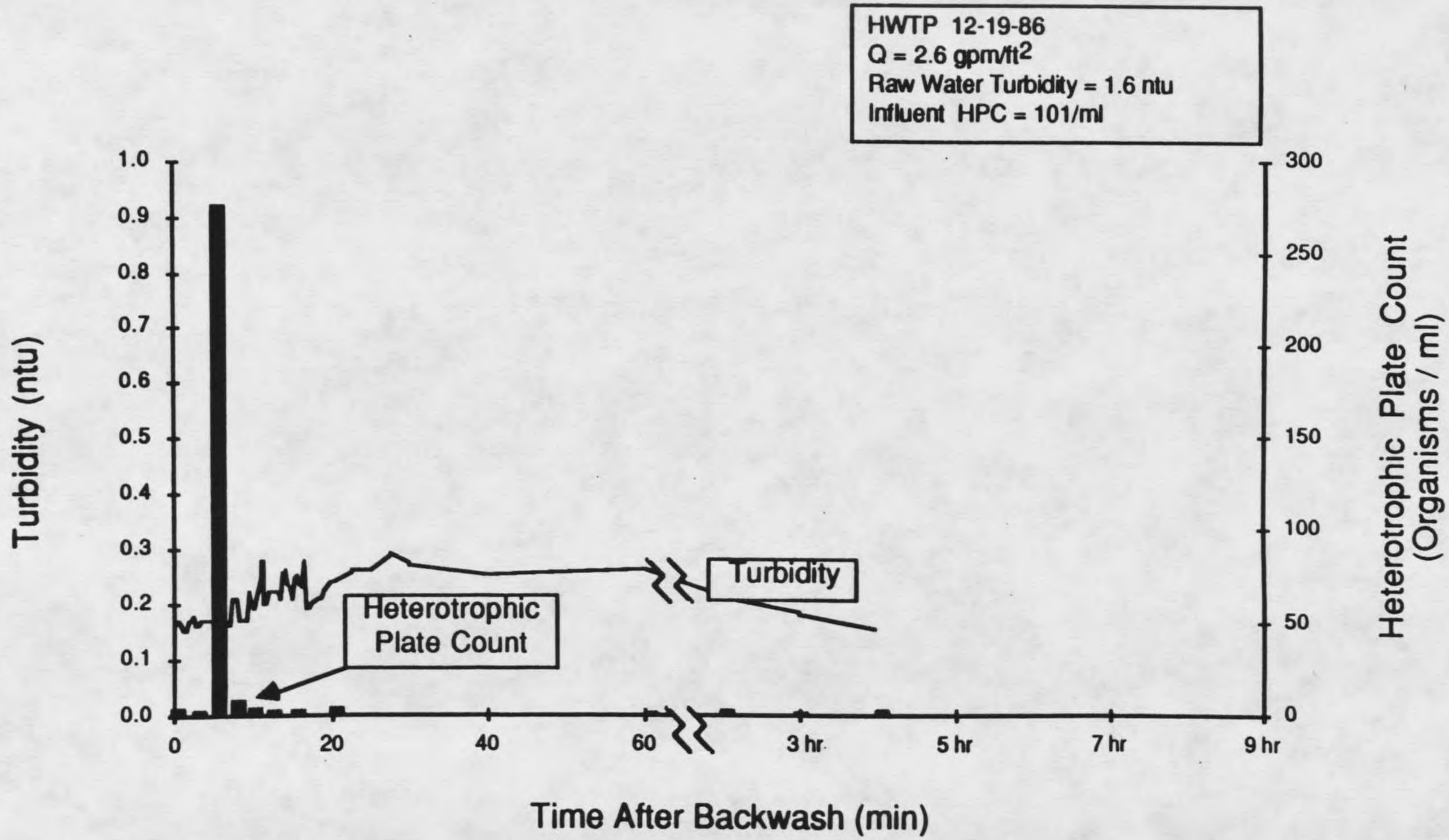

Figure 69. Heterotrophic Plate Counts During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

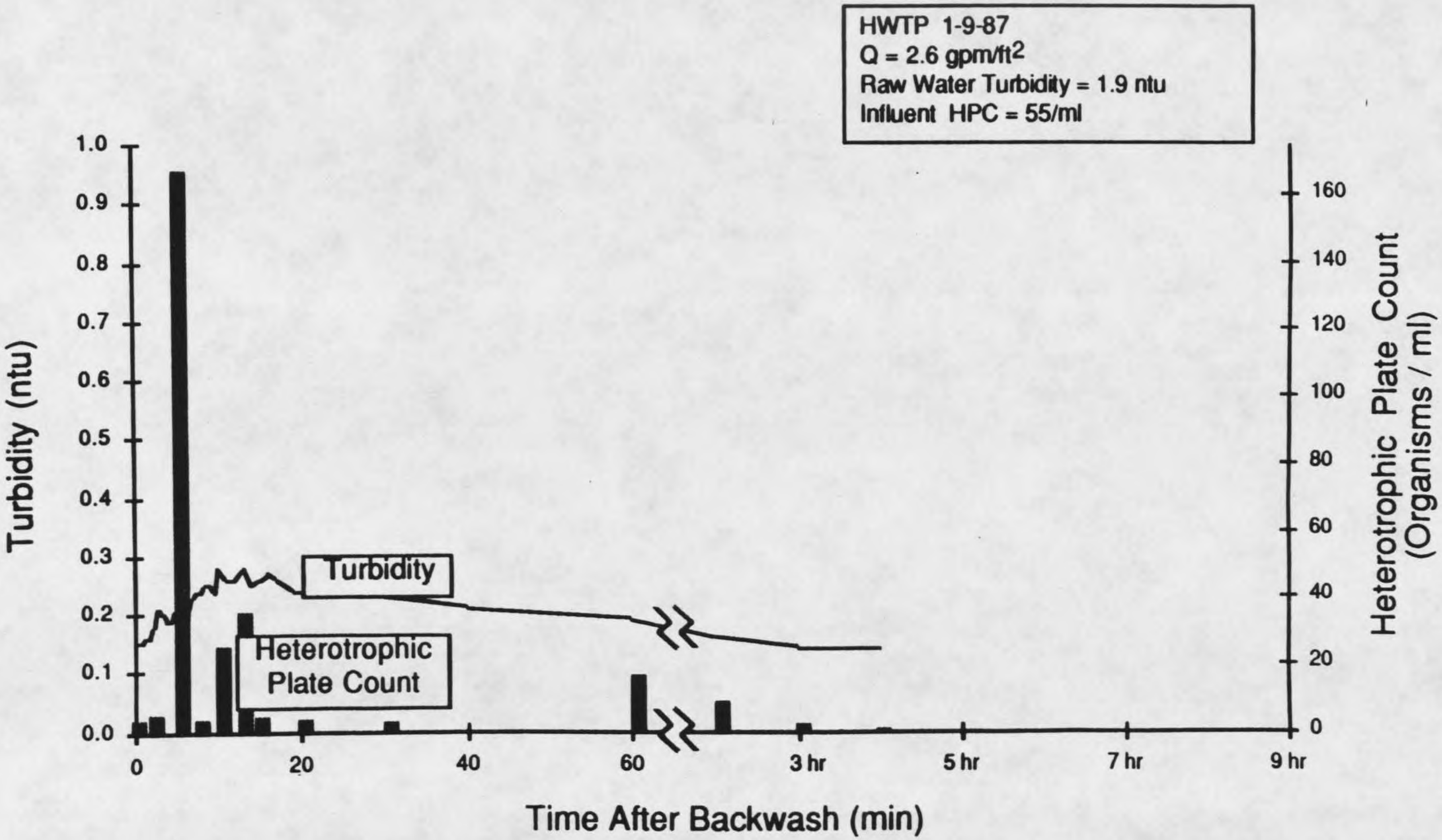

Figure 70. Heterotrophic Plate Counts During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.

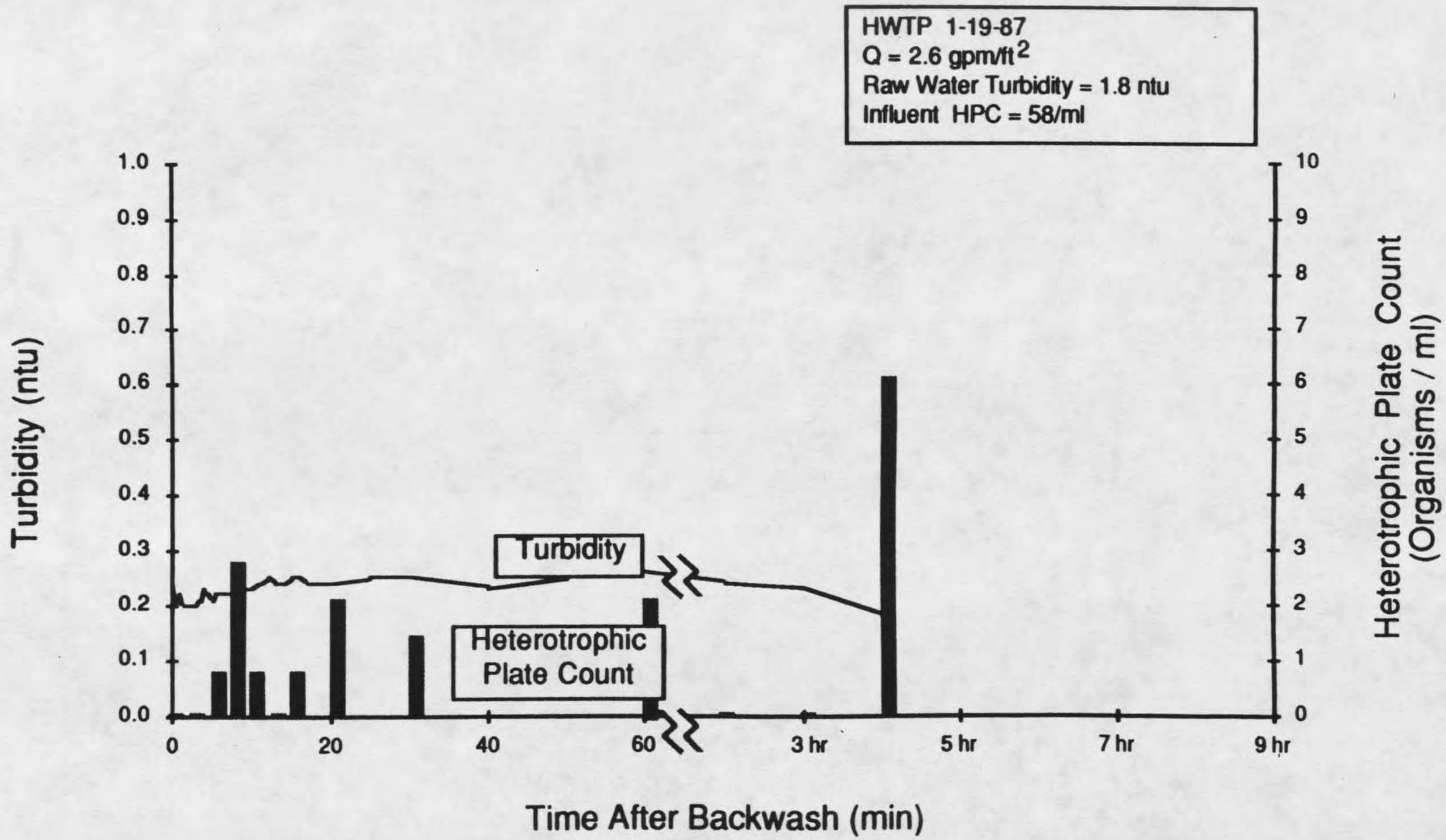

Figure 71. Heterotrophic Plate Counts During Initial Filtration. Missouri River Water Treatment Plant, Helena. Filter detention time = 8.6 min.