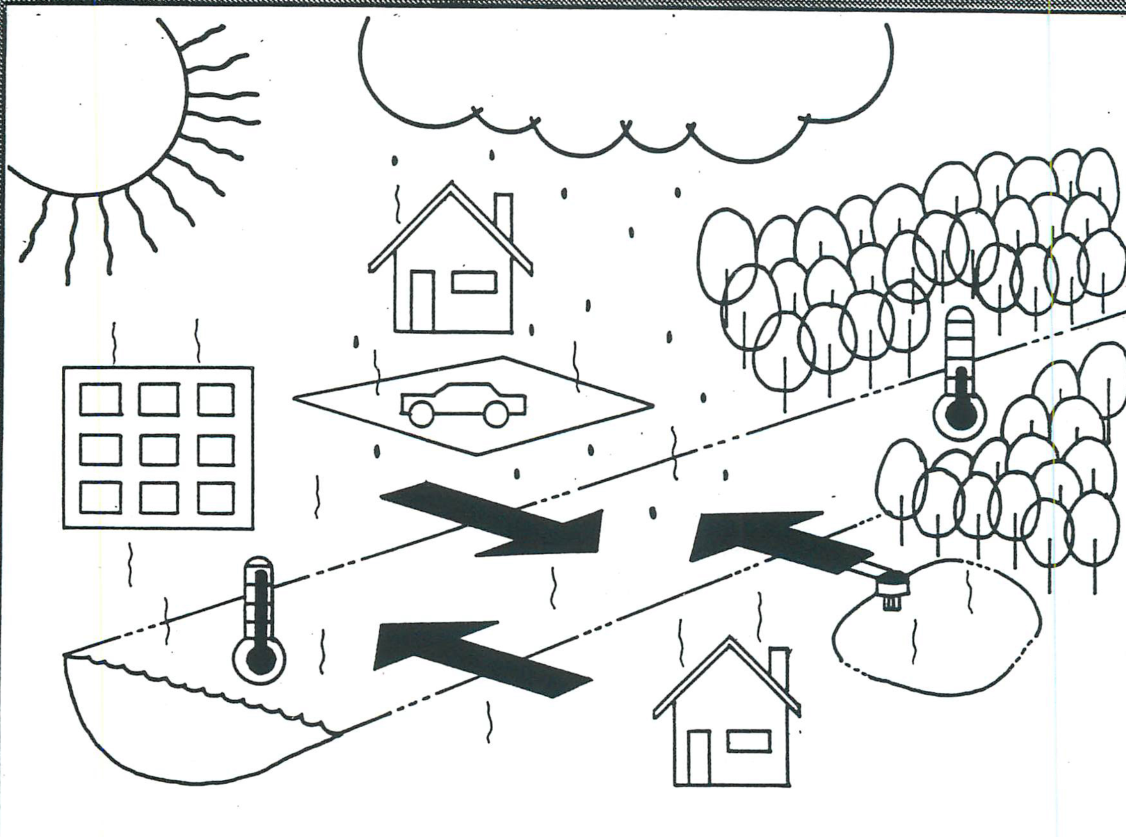
Thermal Impacts Associated With Urbanization and Stormwater Management Best Management Practices



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Administration of the
Maryland Department
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Thermal Impacts Associated with Urbanization and Stormwater Management Best Management Practices

-Final Report-

Prepared for:

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Administration of the
Maryland Department of
the Environment

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Executive Summary

A two-part study was undertaken in 1989 to evaluate the thermal and dissolved oxygen (DO) impacts to aquatic life associated with urbanization and various representative stormwater management Best Management Practices (BMP's). Part one of the study involved both continuous water temperature monitoring and water quality grab sampling at six headwater streams and four stormwater management BMP sites located in the Piedmont portion of the Anacostia River basin. The urban streams studied spanned the entire watershed imperviousness spectrum, and featured undeveloped, as well as, 60 percent impervious sites. The four representative BMP's monitored in the study included: an infiltration facility, artificial wetland, extended detention dry pond, and a wet pond.

Fourteen paired thermograph thermometers were employed to characterize both BMP inflow-outflow temperature relationships, as well as, spatial variations along streams. In addition, a 55 station grab sampling network was established for the purpose of monitoring DO, streamflow and temperature conditions at discrete longitudinal intervals in and along the streams in the study area.

In the second part of the study a comprehensive literature review was performed to evaluate potential temperature and DO impacts at major levels of the aquatic food chain. Major findings of the study are described in the following five sections.

I. Effect of Meteorological and Watershed Land Use Conditions On Free-Flowing Stream Temperatures

Results from the study indicated that the temperature regime of small, free-flowing headwater Piedmont streams is largely determined by the following interrelated factors:

1. Air Temperature and Other Local Meteorological Conditions.

   - Local air temperature had approximately 90 - 95 percent of the time, a greater influence on stream temperature than did stormflow. Notably, the potential for major stream temperature increases grew dramatically when air temperatures remained at or above 80°F for long periods of time. In general, the critical thermal loading season for the streams studied was late May to late September.

   - The amount and intensity of precipitation was an important, though somewhat smaller factor. During the study, small storms which produced little or no runoff generally had little effect on receiving stream temperatures. Sharp, rapid increases in stream temperature were not observed under steady, light precipitation conditions. They were, however, closely associated with warm air conditions which included heavy shower activity.

2. Watershed Imperviousness.

- Imperviousness together with local meteorological conditions had the largest influence on urban stream temperatures. In general, the average water temperature of the urban streams increased in a linear fashion with increasing levels of watershed imperviousness. Results indicated that the average rate of increase was 0.14°F per one percent increase in imperviousness.

- Stream temperatures at the undeveloped watershed responded to storm events by becoming slightly cooler. This was largely due to the drop in air temperatures which accompanied most rainfall events. While this was also generally true of urban streams, as the level of watershed imperviousness increased the streams became progressively more responsive to inputs of stormwater runoff. With increasing imperviousness, the storm-size needed to produce large, stream temperature fluctuations decreased. At a 12 percent watershed imperviousness level over 0.7 inches of rainfall was generally required. In contrast, at a 60 percent imperviousness level, less than 0.2 inches of precipitation was needed to produce a comparable temperature change. It should be noted that stormwater inflow generally produced positive stream Delta-T's. In addition, the potential thermal impact of stormwater runoff on receiving streams increased as the runoff (Q_{in}) to receiving stream flow (Q_r) ratio increased.

- Even at the relatively low 12 percent watershed imperviousness level, neither MDE Class III (68.0°F) or IV (75.0°F) temperature standards could be met 100 percent of the time. Both the frequency and magnitude of temperature standards violations increased with increasing levels of watershed imperviousness.

3. Riparian Canopy Coverage.

- Riparian vegetation plays a key role in insulating small streams from the warming effect of solar radiation. Other studies have shown that the removal of riparian vegetation can raise the summer water temperature of small streams by 11 - 20°F, and can lower winter water temperatures by 5 - 7°F. Results from this study revealed an average positive stream Delta-T of 1.5°F per 100 feet of flow through either open or poorly-shaded reaches.

4. Stream Order/Size.

- It is well known that stream temperature naturally increases in a downstream direction with increasing stream order/distance from the source. In urban watersheds a variety of anthropogenic factors, such as the removal of riparian vegetation, micro-climate changes, and reduction of groundwater inflow, add to the so-called "watershed Delta-T" effect. Monitoring results indicated that the watershed Delta-T effect for a 18 percent impervious, urban third order stream system, is on the order of 1 - 2°F per stream mile. In addition, smaller lower-order urban streams are more responsive to this background watershed effect.

II. Effect of Urban Stormwater Management BMP's On Water Temperature

One of the more revealing findings was that none of the four BMP's monitored where thermally neutral. All four BMP types had positive average total Delta-T's and each violated MDE Class III and IV temperature standards some of the time. Temperature standards violations occurred under both baseflow and stormflow conditions. Wet permanent pools, long periods of extended detention, and poorly shaded pilot and outflow channels contributed greatly to the problem. Specific findings for each BMP type are described below and are additionally summarized in Table 1.

1. Infiltration - Dry pond

- Of the four BMP's, this hybrid facility (which had average and maximum BMP Delta-T's of 2.5 and 7.6°F) produced the smallest Delta-T increases. The infiltration trench portion of the BMP, designed for 0.25 inches of street runoff, worked well during small storms. However, large storm events (i.e., $\geq$ 1.0 inches precipitation) and/or 2 - 3 consecutive days of moderate rainfall generally overtaxed the capacity of the infiltration trench system. This often resulted in the ponding of several feet of runoff in the dry pond area. The facility's defacto extended detention control combined with high incoming solar radiation on the unshaded rip-rap pilot channel, storage pool, and outfall area, produced a 4.0°F Delta-T increase.

- From a water temperature standards perspective, this BMP had the lowest frequency of Class III (68.0°F) and IV (75.0°F) violations. Standards violations were more frequently associated with stormflow conditions. Under stormflow conditions, Class III and IV temperature standards were exceeded 18 and 0 percent of the time, respectively. The BMP's single Class IV violation was a product of a large storm and 53 hours of extended detention.

2. Extended Detention Artificial Wetland

- The average and maximum BMP Delta-T's associated with the wetland were 3.2 and 8.7°F, respectively. Delta-T stormflow temperatures at the wetland were typically lower than baseflow Delta-T temperatures. However, approximately two-thirds of the time the difference between baseflow and stormflow Delta-T's was relatively small (i.e., $\leq$ 3.0 F).

- The shallow depth (mean depth is approximately 18 inches) and small permanent pool volume, relative to the 140 acre contributory watershed, made the wetland and its outflow station

Table 1

Summary: BMP Temperature Performance [1/]

Parameter	Infiltration-Dry Pond	Extended Detention Wetland	Extended Detention Dry Pond	Wet Pond
	BMP Type			
Average Baseflow Delta-T (°F)	2.6	3.9	5.5	9.7
Maximum Baseflow Delta-T (°F)	7.6	8.7	9.7	15.1
Average Stormflow Delta-T (°F)	2.3	2.4	5.2	8.5
Maximum Stormflow Delta-T (°F)	5.0	7.8	11.2	14.0
Average Total Delta-T (°F)	2.5	3.2	5.3	1.1
Maximum Total Delta-T (°F)	7.6	8.7	10.9	9.1
Percent Baseflow - Class III (68°F)	8	60	50	77
Violation of MDE - Class IV (75°F)	1*	15	10	35
Temperature Stds. - Class I (90°F)	0	0	0	0
Percent Stormflow - Class III (68°F)	18	57	48	64
Violation of MDE - Class IV (75°F)	0	5	15	25
Temperature Stds. - Class I (90°F)	0	0	0	0
Maximum observed outflow water Temp (°F)	77.7	80.8	81.9	82.6

1/ - Total Delta-T values shown represent combined baseflow and stormflow temperatures (i.e., all flow conditions).

* - Class IV violation result of defacto extended-detention control.

very responsive to air temperature fluctuations. The wetland's small permanent pool did, however, give it a limited ability to moderate outflow temperatures during certain small storm events. In addition, because the wetland's extended detention capability was extremely limited, it had little influence on outflow station temperature behavior.

- Under baseflow conditions, wetland outflow station temperatures exceeded Class III and IV temperature standards 60 and 15 percent of the time, respectively. In contrast, the same standards were violated approximately 57 and 5 percent of the time, respectively under stormflow conditions. Outflow stations were higher than inflow station temperatures 95 percent of the time.

3. Extended Detention Dry Pond

- The average and maximum BMP Delta-T's associated wi[illegible] the ED dry pond were 5.3 and 11.2°F, respectivel[illegible]. The ma[illegible] Delta-T produced by this BMP was slightly [illegible]igher un[illegible] stormflow conditions (11.2°F) than under basefl[illegible] ondition[illegible] °F). The higher stormflow Delta-T's were the [illegible] ct of [illegible] e influx of relatively warm stormwater runoff [illegible] the f[illegible], b) the partially shaded pilot channel's [illegible] contri[illegible], and c) additional heating of detained wate[illegible] solar [illegible]ation. In addition, the highest Delta-T's wer[illegible] ed duri[illegible] weather. This BMP's 500 foot long pilot c[illegible] prod[illegible] n average positive stream Delta-T of 3.7°F.

- Under stormflow conditions, the ED [illegible] ond vi[illegible] Class III and IV temperature standards 48 a[illegible] perc[illegible] the time, respectively.

4. Wet Pond

- The wet pond's large permanent pool served as an effective heat regulator. In general, the pond had a major [illegible] effect on baseflow temperature. However, during most storm events both pond and outflow station temperatures were depressed. The relatively large permanent pool volume resulted in the pond slowly storing and releasing solar radiation/heat; thus making it slow to respond to air temperature fluctuations. Average summer pond surface water temperatures remained generally over 77°F. Pond waters were noticeably slow to cool-down in late summer/early fall.

- Of the four BMP's, the wet pond had the highest recorded maximum Delta-T (15.1°F). Delta-T baseflow temperatures at the wet pond were higher than stormflow Delta-T's 99 percent of the time. The average baseflow Delta-T (9.7°F) was slightly higher than the average stormflow Delta-T (8.5°F). The pond's rip-rap outflow channel produced an average positive Delta-T increase of 2.0°F.

- From a water temperature standards perspective, this BMP had the highest frequency of Class III and IV temperature standards violations. Under baseflow conditions, Class III and IV standards were exceeded 77 and 35 percent of the time. In contrast, under stormflow conditions the same standards were violated 64 and 25 percent of the time, respectively.

5. Dissolved Oxygen

Results from the dissolved oxygen monitoring portion of the study revealed the following:

- Baseflow DO levels generally do not appear to be a problem in urban streams; even in those draining highly impervious watersheds

- Some oxygen depletion was noted within the artificial wetland, as well as downstream of both it and the wet pond. However, no anoxia was evident.

- DO levels recovered within relatively short distances of the wet BMP's; generally, within 200 - 500 feet.

- No discernible DO sag was observed during stormflow conditions.

III. Biological Implications

In an effort to identify the potential biological impacts associated with temperature regime modification, COG staff conducted a comprehensive two-part literature survey of the water temperature requirements of freshwater biota known or expected to occur in Maryland streams. Part one examined both the principal environmental factors and various human activities which influence the thermal regime of streams. Part two investigated the general thermal requirements of stream biota as well as the potential biological affects associated with thermal regime modification. Potential biological consequences occurring at all general levels of the aquatic food chain were reached. Over 200 references were collected. Special emphasis was placed on identifying the temperature requirements of Maryland freshwater fish. In addition, because of the general controversy surrounding watershed urbanization and trout streams, a separate subsection on trout was included.

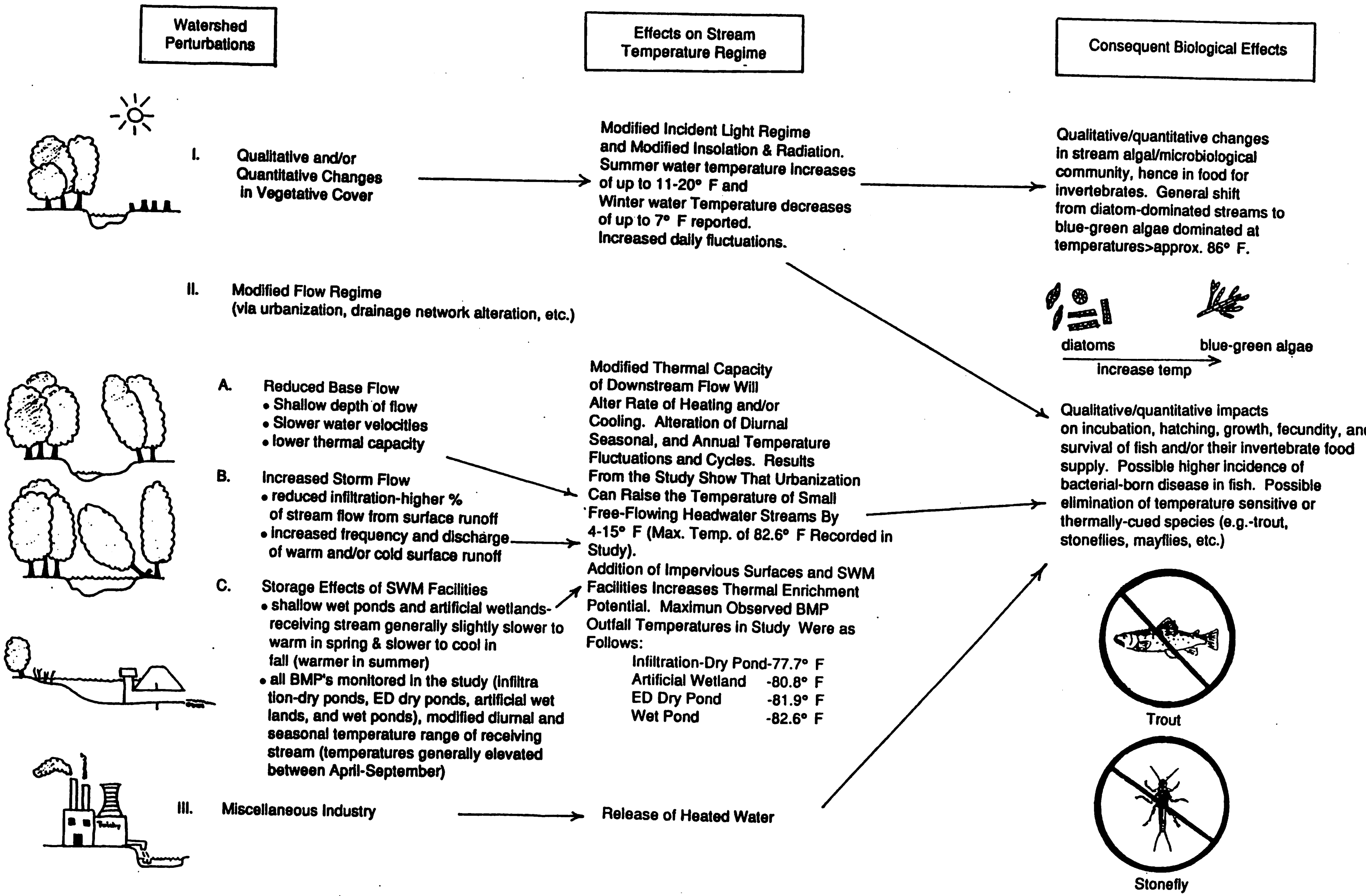
Literature review information together with results from the water temperature monitoring portion of the study were subsequently synthesized. Major findings are presented starting at the bottom of the food chain with algae, and progressing sequentially to fish. In addition, to facilitate reader understanding results have been graphically summarized in Figure 1.

1. Algae.

- Water temperature monitoring results suggest that subtle shifts in the periphyton (attached algae) community species composition would have been expected to have occurred in some of the urban

Figure 1

Summary: General Impacts of Human Activities on Stream Temperature and Biota



streams studied. At all developed watershed and BMP sites, diatoms would have continued to remain the dominant overall algal group. However, certain coldwater and/or light sensitive species may have either declined in numbers and/or been replaced by other, more temperature or light-tolerant species. The scenario would have occurred most likely in stream reaches where considerable thermal enrichment and/or removal of riparian vegetation took place (e.g., wet pond outflow, ED wetland outflow, highly developed urban stream site, and ED dry pond outflow station). In addition, it is probable that green and blue-green algal species would have been represented in greater numbers in the warmer, open-lit sections of these streams.

- While some temperature-related shifts in algal community species composition undoubtedly occurred, it is unlikely that they would have in themselves had a major effect on either the resident macroinvertebrate or fish communities of these urban streams.

2. Macroinvertebrates - Aquatic Insects.

- Results indicate that the thermal enrichment effects produced either through urbanization and/or associated BMP's, would severely effect coldwater aquatic insects. It is most likely that sensitive groups, such as stoneflies, would either be eliminated or severely restricted (for much of the year) at temperature levels comparable to those observed at the moderately and highly developed watershed sites and at the wet pond, ED wetland, and ED dry pond outflow stations. While collectively more temperature tolerant, many mayfly and caddisfly species would similarly be eliminated, severely restricted and/or stressed at the preceding temperature levels.

- Restructuring of the macroinvertebrate community would also occur, with intolerant species and/or groups of insects being replaced by thermally-tolerant ones. It would be expected that tolerant groups such as Diptera (flies & midges) would gain greater dominance in these stream systems. In addition, non-insect species would probably become more abundant. The preceding changes could, if particularly extensive, have a negative impact on the resident fish community.

3. Fish

- Results show that the vast majority of resident fish species would not be affected by the temperature increases produced either through urbanization and/or construction of BMP's. However, coldwater species such as trout would not be expected to survive at temperature levels observed at either the moderately or highly developed watershed sites or at any of the four BMP outfall locations. While generally regarded as being slightly more temperature tolerant than trout, sculpins would only be expected to survive at temperature levels observed at either the lightly developed watershed sites, or below the infiltration -

dry pond. The findings from this study underscore the point that moderate levels of watershed imperviousness and/or the improper introduction of associated BMP's, can have a devastating impact on sensitive coldwater streams and the fish communities which they support.

- All trout species are extremely sensitive to thermal pollution/stress. Sustained elevated water temperatures over 70° F are generally considered to be stressful, while those at or above 77°F are usually lethal. Water temperature monitoring results from the 12 percent impervious Gum Springs tributary indicate that baseflow water temperatures remain safely below levels considered to be stressful to trout. However, under stormflow conditions water temperature exceeds 70°F. The frequency and magnitude of these stress-producing episodes were more severe in Lower Gum Springs, where the temperature regime is negatively affected by the stormwater discharge from the Oak Springs ED wetland. Results further indicate that the thermal regime of Lower Gum Springs may, under stormflow conditions, be approaching the trout supporting temperature threshold for young-of-year and juvenile trout.

IV. Land Use Control Program Implications

Through the process of urbanization, vegetation is removed from watersheds, formerly pervious surfaces are converted to hard, impermeable ones such as rooftops, streets and parking lots, and natural drainage networks are modified to convey runoff more efficiently. These processes act together to alter the thermal regime of urban, headwater streams.

Among the more enlightening results of the study, was the finding that the level of watershed development had the single, greatest anthropogenic influence on the temperature regime of urban, headwater streams. This, as well as other land use control program implications, are briefly described below.

1. Watershed Imperviousness Factor

For urban headwater streams, the level of watershed imperviousness largely determines the magnitude of change from the pre-development thermal regime. As previously noted, results from this study show that mean, summer stream temperatures increase linearly with increasing watershed imperviousness. Importantly, watershed imperviousness has a negative influence on stream temperatures under both baseflow and stormflow conditions.

As seen in Table 2, the frequency of MDE temperature standards violations generally increases with increasing levels of imperviousness. This phenomenon occurs regardless of whether watershed stormwater management controls are present or absent. Reduction of groundwater flows, the urban heat island effect, removal of riparian vegetation, and drainage network alteration are primary causes of the problem.

2. Conflicting Stream Protection and Watershed Development Goals

Table 2. Summary: MDE Water Temperature Standards Violations Versus Watershed Imperviousness

Watershed Development Level	Percent Imperviousness (%)	Percent of Time MDE Temperature Std. Violated (%)			
		Class III (68°F)		Class IV (75°F)	
		Baseflow	Stormflow	Baseflow	Stormflow
Light	12.0	10	5	0	1
Moderate	30.0	25	1	25	1
High	60.0	67	57	12	10

All too often the goal of stream protection conflicts with land use development. Many of the environmental problems caused by urbanization, stream warming for one, cannot be completely mitigated by engineering means. Thus, far greater emphasis on land use control measures is required in sensitive streams.

Results from this study show that stream temperature regime changes occur at relatively low levels of waterdshed imperviousness (i.e., ≤ 12 percent). They also strongly suggest that trout and other coldwater biota will most likely be lost when watershed imperviousness exceeds 12 - 15 percent.

3. Thermal Regime Protection Strategy

It is clear that the long-term protection of thermally sensitive streams requires a holistic watershed management approach which includes, at a minimum, the following water temperature protection elements:

- Land use controls (which govern type, density and location of development within a watershed);
- Riparian/stream buffer requirements;
- Employment of temperature sensitive BMP's and stormwater conveyance systems.
- Long-term water temperature and biological monitoring at strategic stream locations within the watershed; and
- Routine long-term maintenance of BMP's and other associated infrastructure.

Not surprisingly, extraordinary land use, riparian management and stormwater management controls are needed to properly protect the resident aquatic life of MDE Class III streams. The same watershed protection approach is also generally needed, on a case-by-case basis for thermally sensitive Class I and IV stream areas. This stream protection strategy requires that many difficult, and potentially costly, land use decisions be made.

V. Implications for Stormwater Management Programs

Aquatic community species composition and activity in freshwater stream systems is largely regulated by water temperature. In urban streams, the composition and structure of the aquatic community is generally affected by thermal regime modification, as well as, by flow regime, water quality and physical/structural habitat changes.

The results of the water temperature monitoring study have several major implications withregard to current stormwater management practice selection, design and policy. These implications are outlined below.

1. Storm Management Practice Selection

The four BMP's tested were, in ranked order of both Delta-T and outflow temperatures standards performance: 1.) infiltration-dry pond, 2.) artificial wetland, 3.) extended detention dry pond, and 4.) wet pond. By a wide margin the infiltration facility outperformed all other BMP types. The preceding findings strongly support the current MDE stormwater management practice prioritization policy. Clearly, infiltration generally remains the best BMP choice in thermally sensitive watershed areas. At low levels of watershed imperviousness, improper BMP selection can have a major negative effect on the water temperature regime of small, headwater Piedmont streams. This is particularly the case in coldwater stream systems, where the selection of conventional wet and/or extended detention BMP's could conceivably eliminate temperature sensitive species such as trout.

However, results from the study also show that at moderate levels of watershed imperviousness the potentially negative influence of BMP's on the receiving stream's temperature regime is reduced. This is due to the fact that the temperature regime of these streams have been (or will be) modified by the background level of urbanization. Consequently, temperature sensitive biota will, even in the absence of BMP's, most likely be reduced and/or eliminated from these streams. at high levels of watershed imperviousness, the general impact of BMP's on the receiving stream temperature regime is minimal. In these streams, the need for providing high levels of water quality and stream channel erosion control may outweigh temperature concerns. In MDE Class III watershed areas, both extraordinary land use and stormwater management controls are necessary to protect resident stream biota. A similar watershed protection strategy is also generally needed, on a case-by-case basis, for thermally sensitive Class I and IV stream areas. It is also understood that he absence of water temperature and biological data, together with the lack of rapid assessment guidelines often makes the BMP selection process difficult in these areas.

2. BMP Design Feature Considerations

- The thermal performance of the infiltration - dry pond could have been improved had its infiltration design treatment capacity been sized to handle more than 0.25 inches of runoff from roadway areas. Although infiltration systems which are to be located in thermally sensitive watersheds should, as a general rule, be intentionally over-sized there is a finite storm-size which can be treated in this manner. Because of the high probability of large storms and/or several consecutive days of precipitation overtaxing infiltration system design capacity, it is extremely unlike that 100 percent compliance with MDE Class III standards can be achieved in the field.

- Results from the study revealed that unshaded (and/or poorly shaded) pilot and rip-rap outflow channels produced maximum positive Delta-T's of 8.5°F. Shading of these structures via landscaping, other means, would have improved the overall performance of every BMP type tested in the study. In addition, results further indicated that the practice of employing long, wide rip-rap outflow channels should be seriously re-examined. Whenever possible, outflow channels should be heavily shaded. They should also include a deep, narrow baseflow channel to quickly return this water back to the natural stream channel.

- One of the more revealing findings was that long periods of extended detention control can produce BMP Delta-T increases on the order of 4 - 12.0°F. For this reason, the use of extended detention BMP's in thermally sensitive areas should be carefully evaluated. It is further recommended that a 6 - 12 hour detention period limit be established for these areas and that shading of the storage pool area be required.

3. Ability of Current MDE Class I Temperature standards to Protect Aquatic Life

- Results from the literature review portion of the study indicate that the 90°F MDE Class I discharge temperature standard is inadequate to protect a large portion of the biota normally present in headwater Piedmont streams. At the 90°F level, wholesale changes at all levels of the aquatic food chain would be expected to occur. Therefore, it is strongly recommended that new criteria be developed to better protect the aquatic life of Class I streams.

4. Future Research Needs

- The current water temperature class designations are not a reliable guide to the existing or future thermal regime status of headwater Piedmont streams. This is particularly the case for urban streams. Consequently, there is a strong need to develop holistic guidelines and stream assessment procedures for defining appropriate stormwater management options within any Maryland watershed area.

- Water temperature monitoring of parallel pipe and baseflow diversion systems, multiple-port release wet ponds, sand filters, and other promising thermally sensitive conveyance/stormwater management practices is urgently needed.

Introduction

The growing concern over the potential thermal impacts to Maryland's freshwater streams, from both urban stormwater runoff and the various Best Management Practices (BMP's) employed for its control, led the Maryland Sediment and Stormwater Administration to contract the Metropolitan Washington Council of Governments to perform a comprehensive evaluation. As a result, a two-part study was undertaken in 1989 to evaluate the thermal and dissolved oxygen (DO) impacts to aquatic life associated with both urbanization and representative stormwater management BMP's.

Part one of the study involved both continuous water temperature monitoring and water quality grab sampling at six headwater streams and four stormwater management BMP sites located in the Piedmont portion of the Anacostia River basin. The urban streams studied spanned the entire watershed imperviousness spectrum, and featured undeveloped, as well as, 60 percent impervious sites. The four representative BMP's monitored in the study included: an infiltration facility, artificial wetland, extended detention dry pond, and a wet pond. In the second part of the study a comprehensive literature review was performed to evaluate potential temperature and DO impacts at major levels of the aquatic food chain.

For organizational purposes this report has been divided into four main chapters. Chapter one describes study, design, and methodology. The second chapter examines the general thermal effects associated with watershed urbanization, removal of riparian vegetation, increase in stream order/stream size and stormwater management BMP's. In addition to providing detailed information on the thermal characteristics and performance of each of the four BMP's, the chapter provides supplemental information on: thermal loading as a function of flow ratio, stormwater management features which increase water temperature, and results from the dissolved oxygen grab sampling monitoring. In the third chapter, both water temperature monitoring results and literature review findings are synthesized in a comprehensive evaluation of potential biological impacts. The fourth and final chapter, discusses the implications of the study's findings on both stormwater management and land use control programs.

Chapter I. Study Design and Methodology

The study was designed to evaluate potential thermal and dissolved oxygen (DO) impacts associated with representative stormwater a agement BMP's currently in use throughout the state (i.e., wet ponds, ar ial wetlands, extended detention dry ponds, and infiltration). In ad , the general effects of both the level of watershed urbanization and ian management practices on stream temperature were investigated, tog with potential biological implications.

In order to meet the preceding objectives tudy featuring thre major elements, or tasks, was developed. Un he fi k, a continuou water temperature monitoring network was ated ovide necessar baseline data. Second, a water quality grab ampling n was establishe to provide baseline dissolved oxygen, stream flow, and ater temperatur data. Last, a comprehensive literature search was rmed to identif water temperature requirements of freshwater biota, at general levels of the food chain, and relate them to water temperature mon ing results.

The following sections describe in greater detail he study design, sampling techniques, and calculations employed in the study.

Development of a Comprehensive Field Monitoring Network

A. Site Selection

Metropolitan Washington Council of Governments staff (COG) in consultation with MDE, MdDNR, and local agency staff identified the following six representative study categories for monitoring:

1. Wet pond;

2. Artificial wetland;

3. Extended detention dry pond;

4. An innovative stormwater management facility which incorporates temperature mitigation features;

5. An urban stream draining a small, highly impervious and uncontrolled watershed; and

6. A reference stream draining a small undeveloped watershed.

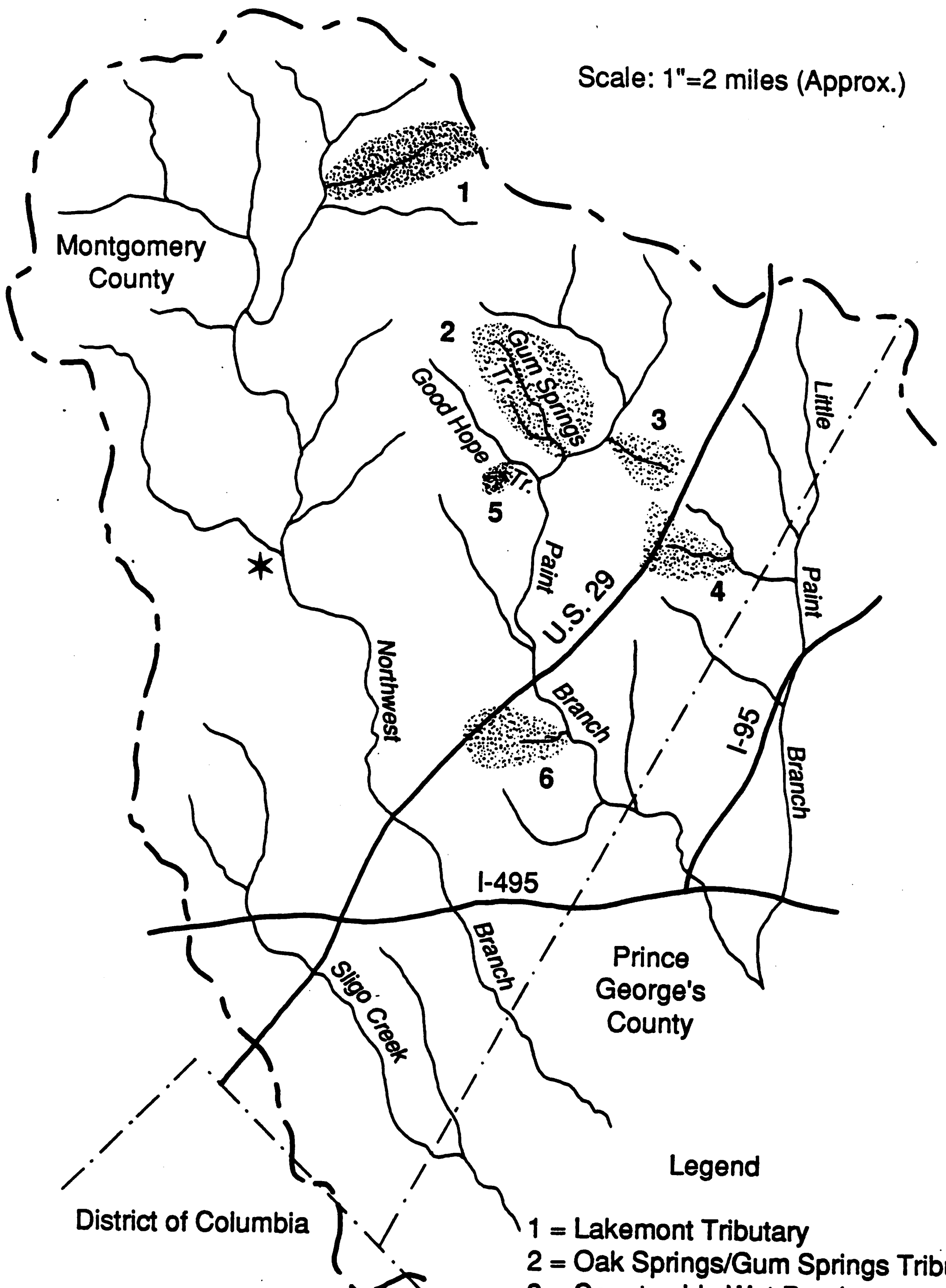
An inventory of possible candidate sites for each of the preceding six categories was conducted within the Maryland portion of the Anacostia River basin. Each candidate site was carefully screened and ranked according to the following criteria: MDE water use class designation, drainage area, watershed land uses, stream discharge, stormwater and stormdrain conveyance system, and representativeness and access. After consultation with MDE, COG staff selected a total of six sites from the inventory for subsequent continuous water temperature monitoring and water quality grab sampling. Study area locations are shown in Figure 1, and the general characteristics of each site are summarized in Table 3. Additional information on each site can be found in Appendix A. A brief description of each study site is provided as follows:

1. **Lakemont tributary.** This reference Piedmont stream is located in the headwaters of Northwest Branch, an MDE Class IV recreational trout stream area. The Lakemont tributary drains an undeveloped watershed area of approximately 400 acres. During the late 1970's much of the subwatershed was used as a sludge trenching area. However, since 1978 the disturbed portions of the watershed have remained fallow. Forest and old abandoned fields are now the predominant land uses in the study area. The Lakemont tributary, which is approximately 8-9 feet wide is heavily shaded by the mixed-age hardwood forest through which it flows. Average stream baseflow during the study period was 0.9 cfs.

2. **Oaksprings/Gum Springs tributaries.** The Oaksprings tributary is a small feeder branch of the Gum Springs tributary. Both streams are designated by MDE as Class III natural trout waters. The Oaksprings tributary, which flows through a mixed-age hardwood forest, drains a developed 140 acre watershed. Principal land uses in the catchment include 0.25-0.5 acre lot single family residential development and

FIGURE 2

WATER TEMPERATURE MONITORING LOCATIONS



Legend

1 = Lakemont Tributary
2 = Oak Springs/Gum Springs Tributaries
3 = Countryside Wet Pond
4 = Tanglewood ED Dry Pond
5 = Fairland Ridge Infiltration-Dry Pond
6 = White Oak Tributary
✱ = NOAA Weather Station (Glenmont, Md.)

Table 3. Summary: General Study Site Characteristics

Study Location	Station Type	Watershed	MDE Water Use Class	Physio-graphic Province	Watershed Drainage Area	Major Land Uses 1/	Watershed Imperviousness (%)	Stream Gradient (%)	Avg. Stream Width (ft.)	Avg. Baseflow (cfs)	Pond Surface Area (ac))	Max. Depth of pond (ft.)	Method of Extended Detention Control
1. Lakemont Tributary	Reference Stream	Northwest Branch	IV	P	400.0	F, OF	1.0	1.5	8 - 9	0.86	-	-	-
2. Oaksprings/ Gumsprings													
a. Oakspring Trib.	Artificial wetland	Paint Br.	III	P	140.0	TH, SFR	18.0	2.7	3 - 6	0.11	1.0	4.0	Notched, wood weir flashboard
b. Gum Springs Trib.	Trout Stream	Paint Br.	III	P	620.0	SFR, F, OF TH	12.0	2.0	8 - 10	0.99	-	-	-
3. Countryside	Wet Pond	Paint Br.	III	P	165.0	SFR, LE, F, C	12.0	2.3	3 - 6	0.25	1.5	8.0	-
4. Tanglewood	ED Dry Pond	Little Paint Br.	I	P/C	195.0	TH, SFR O, F	30.0	2.3	5 - 10	0.26	3.0	-	gate valve
5. Fairland Ridge	Dry Pond w/Infiltration Trenches	Paint Br.	III	P	25.0	SFR	18.0	4.7	2 - 3	0.05	0.5	-	*
6. White Oak Tributary	Urban Stream	Paint Br.	III	P/C (Fall-line)	225.0	C, GA, F	60.0	3.9	8 - 12	0.35	-	-	-

Key Appreviations:

1/ P = Piedmont; C = Coastal Plain
F = Forest; OF = Old Field; TH = Townhouse; SFR = Single Family Residential (0.25 -. 05 ac. lot);
C = Commercial; GA = Garden Apts;

LE = Large Estates (> 2 ac); O = Office Park

* = Defacto extended detention control.

townhouses. In addition, two SWM facilities, which are separated by a distance of approximately 1800 ft., are located on the stream. The upper Oaksprings pond is an old farm pond that has a surface area of approximately 0.5 acres. The lower Oaksprings pond which was monitored in the study, is a 1.0 acre artificial wetland with extended detention control. A notched wooden weir - flashboard system provides approximately 1.0 acre-foot of extended detention storage. The Oaksprings wetland, which was constructed in 1986, supports a diverse wetland plant community and includes numerous emergent and submerged species. This wetland is located approximately 500 feet upstream of the confluence with the Gum Springs tributary. The Oaksprings tributary enters Gum Springs approximately 1900 feet upstream from the Gum Springs/Paint Branch confluence.

Gum Springs, which drains a 620 acre watershed area, is well-known for its ability to support a natural self-sustaining brown trout population. Principal land uses in this subwatershed include 0.25 - 0.5 acre lot single family residential development, townhouses, old abandoned fields, and mixed-age hardwood forest. Overall watershed imperviousness is approximately 12.0 percent. The stream, which has an average baseflow of approximately 1.0 cfs, is well-shaded along its entire length.

3. **Countryside Wet Pond.** The Countryside wet pond drains a 165 acre MDE Class III watershed area consisting of large residential estates, 0.25 -0.5 acre single family residential development, mixed-age hardwood forest, and a small commercial shopping area. Watershed imperviousness is approximately 12.0 percent. The pond, which has a surface area of approximately 1.5 acres, underwent a major retrofit in 1988. Retrofit work included the replacement of the original rusted-out metal riser and barrel with a concrete structure, dredging, and establishment of fringe marsh habitat. It should be noted that pond waters are released approximately 2.5 feet below the normal pool elevation via a reverse sloping 8 inch diameter pipe. Baseflow to the pond is approximately 0.25 cfs. The Countryside tributary is well-shaded both upstream and downstream of the pond. Waters discharged from the pond flow through approximately 1200 feet of mixed-age hardwood forest before entering Paint Branch.

4. **Tanglewood Extended Detention Dry Pond.** Constructed in 1983, the Tanglewood SWM facility is a 3.0 acre, extended detention dry pond serving a 195 acre MDE Class I watershed area. Principal land uses in the catchment include townhouses, 0.25 - 0.5 acre single family residential development, office park development, pasture/old fields, and mature hardwood forest. Watershed imperviousness is approximately 30 percent. The Tanglewood tributary is well-shaded both upstream and downstream of the SWM facility. The stream, which has an average baseflow of approximately 0.26 cfs, is a tributary of the Little Paint Branch.

5. **Fairland Ridge Stormwater Management Facility.** This innovative dry SWM facility, which became operational in 1987, provides both water quantity and quality control for a 25 acre, MDE Class III watershed area. Water quality control for the existing 0.25 - 0.5 acre lot residential development is provided through a series of stilling basins, grass swales, and infiltration trenches located in the terraced side slopes of the pond. The three infiltration trenches present in the pond were sized to treat the first 0.25 inches of runoff from the street portion of the development.

During the course of the study it became obvious that one of the three infiltration areas present was incapable of infiltrating any runoff. In fact, this bowl-shaped infiltration area was observed to pond water for months at a time. A second observation made during the study was that the pond provides, via its 8 inch diameter low-flow orifice, defacto extended detention storage for the larger storm events which exceeded the infiltration trench system's capacity.

The Fairland Ridge SWM facility also includes a spring, bearing the same name, which originates in the vicinity of the pond's lowflow orifice. Waters form the spring flow approximately 600 feet whereupon they join the Good Hope tributary of Paint Branch. The small 2 - 3 foot wide spring meanders through a partially forested riparian area. Baseflow produced by the spring is a relatively constant 0.05 cfs.

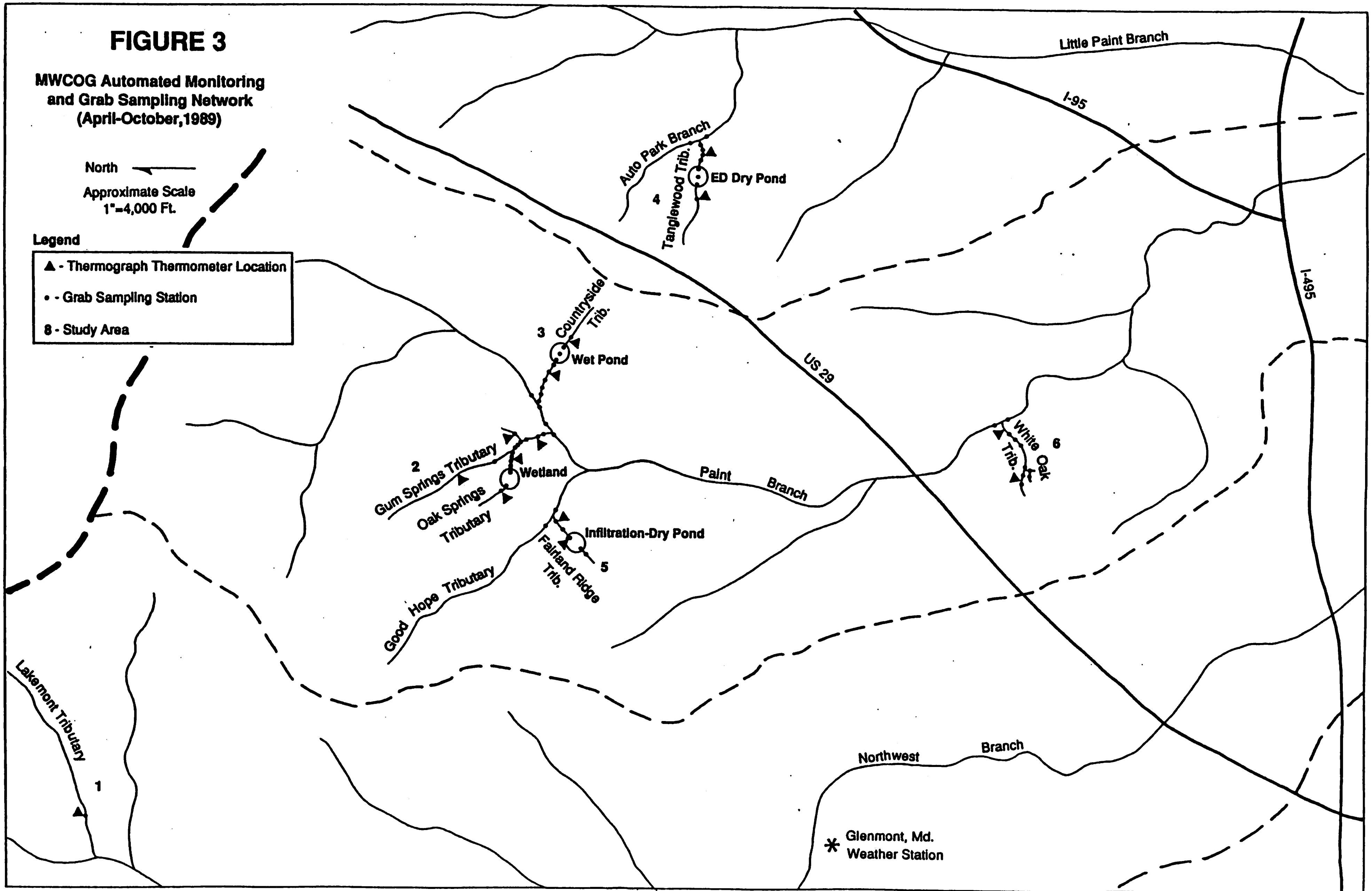
6. **White Oak Tributary.** This severely degraded, urban stream drains an intensively developed 225 acre MDE Class III watershed. Principal land uses in the contributory drainage basin include a major commercial shopping center area, garden apartments, and mature hardwood forest. For all intents and purposes this watershed area has no SWM controls. Although the headwaters of the fall-line stream have been piped, approximately 2500 feet of open stream channel remain. The majority of the remaining lower open section of stream flows through a mature hardwood forest. In character with fall-line streams, the White Oak tributary is boulder-strewn and contains numerous rock outcroppings and ledges. Stream width averages 8 - 12 feet and baseflow is approximately 0.35 cfs.

B. Continuous Water Temperature Monitoring

Characterization of the thermal regime of each of the six study areas was accomplished via the systematic employment of paired Ryan TempMentor recording thermograph thermometers. COG staff, with assistance from MdDNR Freshwater Fisheries, developed a continuous water temperature monitoring network consisting of 14 thermograph thermometer stations. The stations were strategically located so as to measure inflow-outflow temperature conditions, at the four BMP study sites, and identify spatial temperature variations along the streams. The general location of the 14 continuous temperature monitoring stations is shown in Figure 3.

FIGURE 3

MWCOG Automated Monitoring and Grab Sampling Network (April-October,1989)



Monitoring Period

All 14 thermograph thermometers were installed and operated, by COG staff, for the April 25 through September 20, 1989 period. Each unit was programmed to record water temperatures on a 20 minute time interval. This time interval was selected so as to measure and characterize stream temperature responses to small storm events in a uniform manner. Units were allowed to remain in the field for as long as 64 days before being removed. Stored temperature data was retrieved from each unit via downloading into an IBM compatible personal computer. The 14 thermograph thermometers were subsequently redeployed and returned to their original field locations within 48 hours. This process was repeated for each of the three deployment periods used in the study. Specific information for each of the three deployment periods is contained in Appendix B.

Equipment Selection and Field Installation

Ryan thermograph thermometers were selected for use in the study on the basis of the following attributes: 1.) the units feature an easily programmable sampling time interval ranging from one second to two hours, 2.) the units may be left unattended in the field for months at a time, and 3.) stored data can be quickly downloaded from the unit into a computer for further processing and analysis.

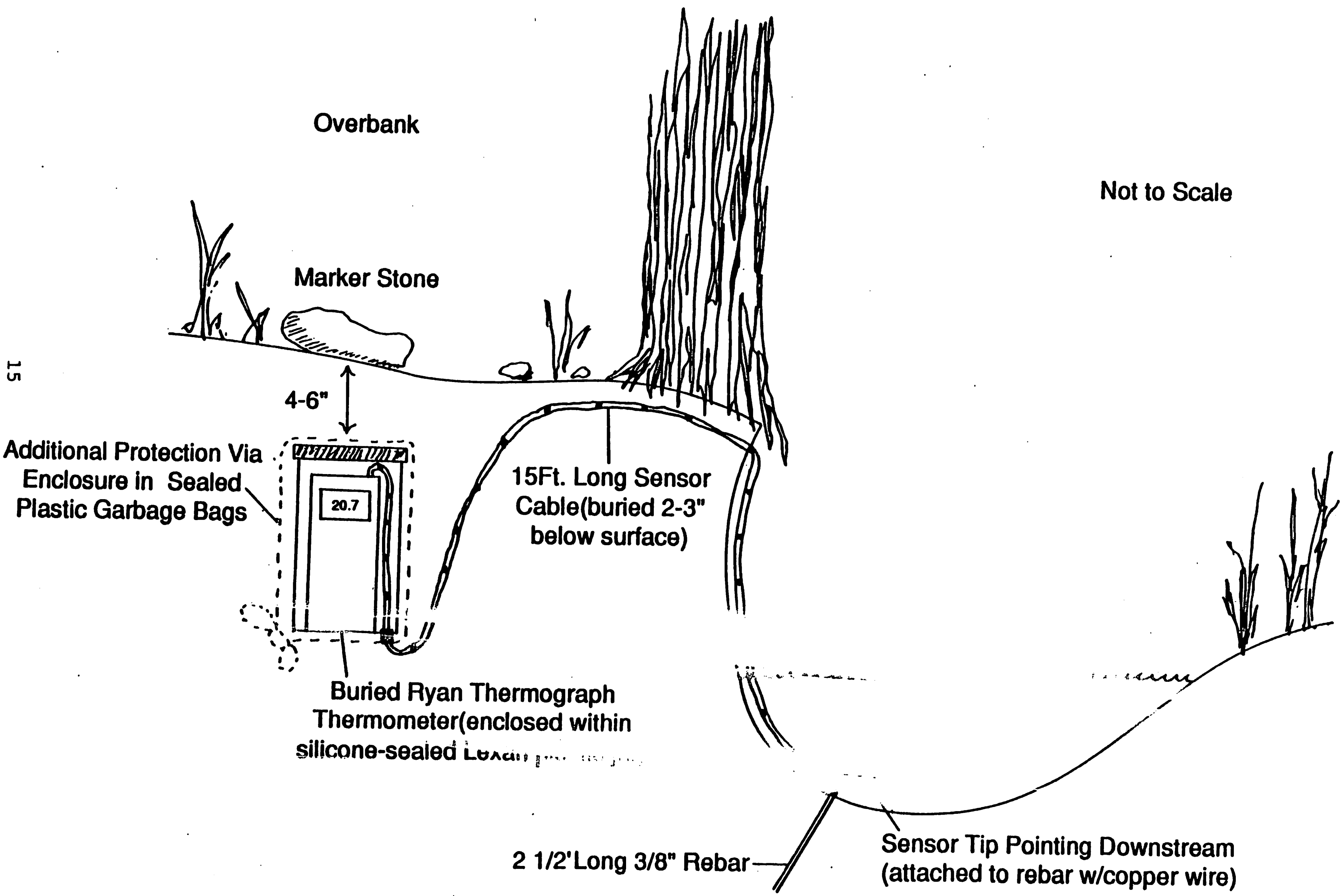
Each thermograph thermometer was placed into a silicone-sealed, screw-top Lexan plastic jar, then tightly sealed in two or more plastic garbage bags. The units were carefully buried, 4 - 6 inches below ground level, in an overbank area so as to reduce the risk of damage or loss from flooding and/or vandalism. Actual stream water temperature readings were made via an associated 15 foot long sensor cable that extended from the buried unit into the stream. The buried sensor cables were attached to steel rebars driven into the stream bottom. All cables were located in well-shaded undercut bank areas of the stream, where depth of flow was sufficient to keep the sensor tip completely submerged at all times. The basic sampling configuration used during the study is depicted in Figure 4. Each site was inspected by COG staff on a weekly basis.

C. Climatological Information System and Data Summary

Due to budgetary constraints rainfall, air temperature, and other pertinent climatological data was obtained from the National Oceanographic and Atmospheric Administration (NOAA) Independent Weather Station Network. After careful review of existing NOAA stations in the vicinity of the six study areas, COG staff selected the Glenmont, Md. station as its primary reference weather station (Figure 3.). This decision was based upon the following: 1.) of the 14 stations examined, the Glenmont station's location was closest to the center of the six study areas, 2.) the station has provided comprehensive and reliable meteorological data for over 10-years, and 3.) the physical setting of the station, i.e., elevation and stream valley location, is similar to those of the study sites. Furthermore, it should be noted that meteorolgical data for a select group of storm events

FIGURE 4

THERMOGRAPH THERMOMETER SAMPLING CONFIGURATION



was obtained from one or more of the neighboring, 13 sister stations.

April - October, 1989 Climatological Summary

A comparative summary of climatological conditions, April - October 1989. at both the Glenmont station and Washington National Airport (DCA) are presented in Table 4. Included for reference in the table are 30-year historical levels for DCA. Additional climatological information may be found in Appendix D.

Table 4. Summary: 1989 Climatological Data

Parameter	April	May	June	July	Aug.	Sept.	Oct.
1. Max. Temperature (^{o}F)							
Glenmont	78.0	87.0	91.0	92.0	92.0	90.0	83.0
DCA	80.0	87.0	95.0	96.0	94.0	96.0	83.0
DCA (30-yr)	95.0	97.0	101.0	104.0	103.0	101.0	94.0
Avg. Maximum (^{o}F)							
Glenmont	63.1	70.7	80.7	82.2	80.5	75.6	67.9
DCA	64.8	72.8	84.7	85.7	84.7	79.5	70.4
DCA (30-yr)	67.1	75.9	84.0	87.9	86.4	86.4	68.9
2. Min. Temperature (^{o}F)							
Glenmont	27.0	37.0	53.0	54.0	50.0	38.0	34.0
DCA	35.0	44.0	60.0	62.0	57.0	46.0	38.0
DCA (30-yr)	24.0	34.0	47.0	54.0	49.0	39.0	29.0
Avg. Minimum (^{o}F)							
Glenmont	40.3	51.0	64.5	66.9	64.9	58.0	45.0
DCA	45.9	55.3	68.9	70.8	69.4	63.2	50.5
DCA (30-yr)	46.2	56.1	65.0	69.9	68.7	62.0	49.7
3. No. Days Max. Temp. > 90 ^{o}F							
Glenmont	0	0	2	2	2	1	0
DCA	0	0	4	9	7	2	0
DCA (30-yr)	-	1.4	7.4	13.1	10.3	4.2	0.1

Table 4. - Cont'd -

Parameter	April	May	June	July	Aug.	Sept.	Oct.
4. No. Days Max. Temp. 80 - 89°F							
Glenmont	0	9	15	19	16	8	3
DCA	1	10	21	18	18	15	3
DCA (30-yr)	-	-	-	-	-	-	-
5. Days Precip. > 0.01"							
Glenmont	9	17	14	9	10	12	10
DCA	9	15	13	12	5	10	8
DCA (30-yr)	9.8	11.2	9.5	9.8	9.2	7.6	7.4
Days Precip. > 1.0"							
Glenmont	0	3	3	2	0	1	0
DCA	0	3	1	2	0	2	1
DCA (30-yr)	-	-	-	-	-	-	-
Normal or Total Precip. (in.)							
Glenmont	3.39	10.93	6.09	5.58	0.89	4.51	5.00
DCA	3.50	7.77	6.02	5.66	1.15	6.68	5.48
DCA (30-yr)	2.93	3.46	3.35	3.88	4.40	3.22	2.90
Greatest Precip. in 24 hrs (in.)							
Glenmont	0.65	4.68	1.21	1.53	0.58	1.06	0.98
DCA	0.99	2.24	1.40	1.41	0.95	1.84	1.83
DCA (30-yr)	3.08	3.43	7.19	4.69	6.39	5.31	4.98

Table 4. - Cont'd -

Parameter	April	May	June	July	Aug.	Sept.	Oct.
No. Days Clear Skies							
Glenmont	-	-	-	-	-	-	-
DCA	4.0	2.0	7.0	4.0	4.0	6.0	13.0
DCA (30-yr)	7.1	7.3	7.8	7.7	9.1	10.1	11.0
No. Days Cloudy Skies							
Glenmont	-	-	-	-	-	-	-
DCA	12.0	17.0	15.0	12.0	16.0	17.0	10.0
DCA (30-yr)	14.0	13.8	11.3	11.4	11.8	11.7	12.5

From a historical perspective, the April-July portion of the study was notably cooler and wetter than normal. In particular, the month of May was exceptionally wet with 10.93 inches of rain recorded at the Glenmont Station. Of this total amount, 4.6 inches of rain fell during one 24-hour period (May 6-7). Runoff from this near 10-year frequency storm event resulted in severe flooding of both study area and local streams. Flood waters severely damaged one of the 14 thermograph thermometers, requiring replacement of the unit. The storm also damaged two other thermographs thermometers resulting in the loss of stored water temperature data.

While the spring and early summer months were wetter than normal, extremely dry and cloudy conditions occurred in August. Precipitation in August totalled only 0.89 inches at Glenmont. This amount was 3.51 inches below reported 30-year historical averages for the WMA. Precipitation, temperature, and cloudiness were generally higher than normal in September. As seen in Table 4, monthly average temperatures, precipitation, and the number of clear days in October were also above 30-year historical averages for the WMA.

D. Water Quality Sampling

Under this task, COG staff developed and operated a 55 station water quality grab sampling network (Figure 3). The network was specifically designed to measure DO, stream flow, and air and water temperature conditions at discrete longitudinal intervals in and along the streams in the study area. Grab sampling was conducted, on a weekly basis, during the June 16 - October 20, 1989 period. In addition, limited stormflow monitoring was performed during the same period.

DO measurements were made in the field via the employment of a YSI-57 (Yellow Springs Instrument) dissolved oxygen meter. Instrument accuracy was maintained during the four month sampling period through weekly calibration and spot checks against Winkler-titration sampling results.

Stream discharge was determined via the Embody Float Method (Embody, 1927). This technique uses the following equation for calculating flow:

$$\text{Discharge (Q)} = \frac{W \times D \times a \times T}{L}$$

where:

W = stream width (ft.)
D = stream depth (ft.)
a = roughness coefficient for stream bed (0.9 rough bottom, 0.8 smooth bottom)

T = travel time of float (sec.)
L = distance travelled by float (5 ft.)

Twelve flow measuring stations, each having a standard five foot flow length were established. Station locations were selected on the basis of representativeness of stream flow condition, ease of access, and ability to maintain relatively uniform cross-sectional areas. At each station, nine or more depth measurements, three wetted perimeter measurements, and three timed-floats were made per stream flow calculation. Because of the similarity in stream bed roughness, an 'a' value of 0.9 was used at all stations throughout the study.

E. Delta-T Water Temperature Analysis and Calculation

In order to quantify the degree of change in water temperature resulting from either the passage of stormwater runoff through a BMP, or from an undeveloped reference stream to a highly urbanized stream, a uniform comparative approach was required. Since these site specific changes may be expressed as a Delta-T value, water temperature analyses in the study were performed using this approach. The Delta-T method features direct comparisons of observed temperatures between a subject station(s) and some known reference at specific points in time.

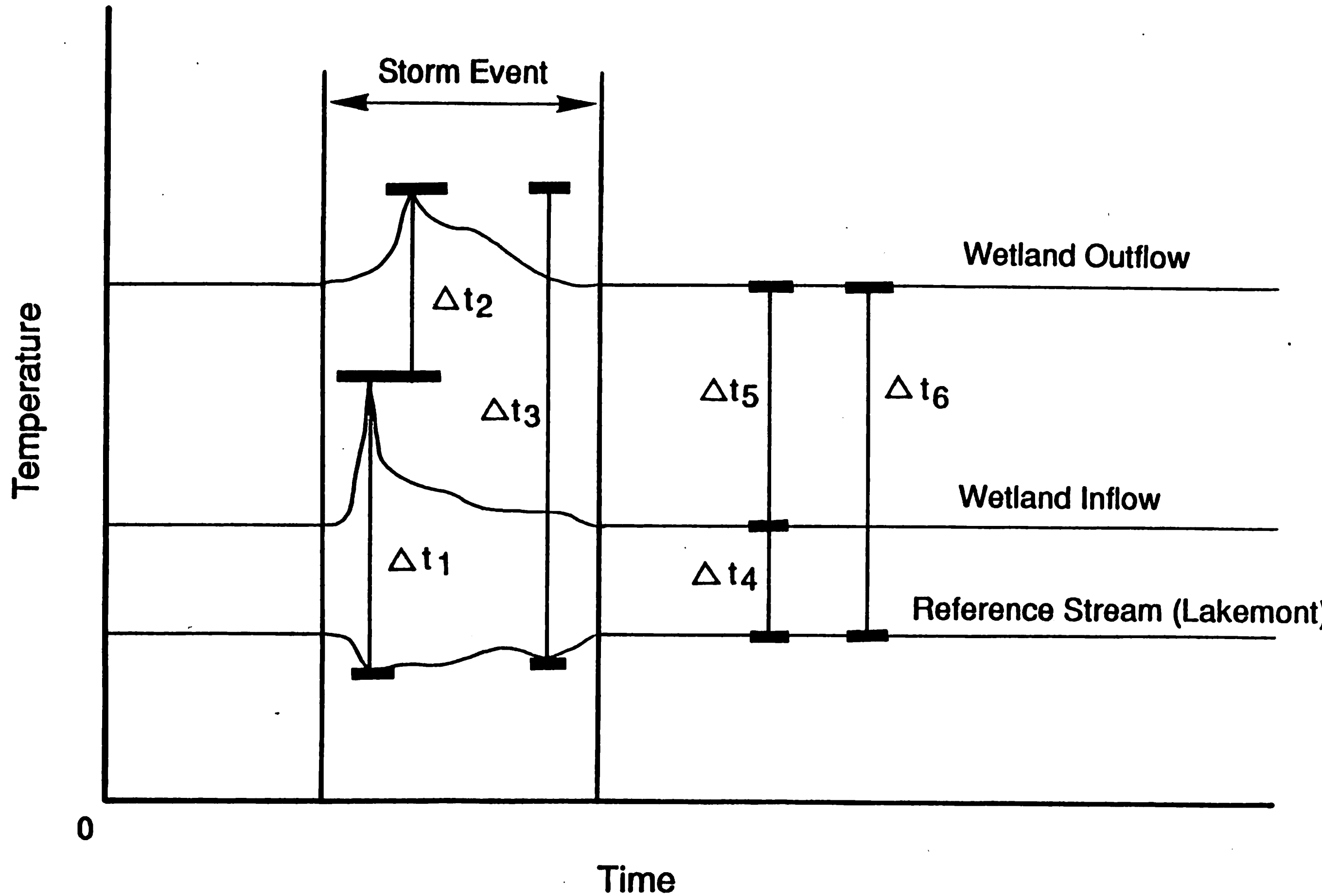
For reasons already stated, the Lakemont tributary was chosen as the standard reference station against which all other study stations were compared. In addition, in order to quantify the inflow-outflow temperature relationships for a particular BMP, a second series of Delta-T comparisons was required. This second series involved the establishment of the SWM inflow station as the reference station. An example of the possible water temperature comparisons under the study's Delta-T approach is illustrated in Figure 5.

Delta-T Calculation

The Delta-T temperature, which can be either positive or negative, was calculated by taking the mean hourly temperature for both the subject and reference stations, then subtracting the reference station temperature from that of the subject station. An example of a standard one-hour Delta-T

FIGURE 5

Δ t SCENARIOS FOR OAKSPRINGS ARTIFICIAL WETLAND



calculation for the Countryside Inflow station is presented below:

Station	20 Minute Temperature Readings (°F)	Mean Hourly Temp. (°F)	Difference Btwn. Reference & Subj. Station (°F)
Lakemont (Reference)	64, 65, 66	65	+ 4.0
Countryside Inflow (Subject)	68, 69, 70	69	

The one-hour Delta-T for the Countryside Inflow station is positive 4.0 °F.

A minimum of 24 hourly Delta-T's, per day, were calculated for each subject station. Where possible, efforts were made to relate Delta-T values to environmental conditions such as rainfall, air temperatures, and stream discharge.

F. Percent of Time Plots

In addition to the Delta-T analyses, data from each continuous monitoring station was statistically analyzed and graphically depicted to show the percent of time water temperatures remained at, above, or below some particular temperature of interest (e.g., 68 °F MDE Class III temperature standard). Percent of time plots were generated for baseflow, stormflow, BMP performance, and climatological influence scenarios. These plots, along with the Delta-T analyses, served as the analytical backbone of the study.

G. Data Manipulation - SAS Architecture

The Statistical Analysis System (SAS), which is a mainframe computer system for data analysis, was used to statistically analyze and graphically depict water temperature and climatological data. A series of SAS programs were specifically written to accomplish the following general objectives:

1. Organize data by date, time, sampling station location, station type, and stream system;

2. Develop, through the integration of water temperature and precipitation data, baseflow and streamflow water temperature data sets;

3. Compute BMP and stream Delta-T's under baseflow, stormflow, and/or total flow conditions;

4. Statistically analyze, via the PROC UNIVARIATE (procedure analysis package), water temperature data sets; and

5. Graphically depict data.

H. Literature Review of Water Temperature Stress and Aquatic Communities

In an effort to identify the potential biological impacts associated with temperature regime modification, COG staff conducted a comprehensive literature survey of the water temperature requirements of freshwater biota known or expected to occur in Maryland streams. Over 200 references, in one or more of the following categories, were collected:

- The thermal regime of natural streams - their general characteristics and the environmental factors which influence them;
- The general impact of human activities, particularly urbanization, on the temperature regime of streams; and
- Potential water temperature-related effects on the aquatic food chain of streams.

Special emphasis was placed on identifying the temperature requirements of Maryland freshwater fish. One of the major accomplishments of this subtask was the gathering and summarizing of water temperature-related findings for 63 fish species. The major findings of this overall effort are included in Appendix C. of the report.

Chapter II. Monitoring Results

A. General Effects of Watershed Urbanization, Riparian Cover, Stream Order, and Stormwater Management BMP's

Water temperature in natural streams is greatly influenced by factors such as climate, riparian vegetation, hydrology, topography, and stream order/distance from source. Development within natural watersheds s[illegible]y increases average stream temperatures in summer and depresses them in winter (Gray & Eddington, 1969; Hewlett & Forston, 1982). Concurrent temperature differences between sites along urban streams have been shown to vary as much as 14 - 20^{o}F on hot, sunny summer days (Pluhowski, 1970). These large temperature differences have been attributed to a wide variety of urban factors, including the removal of vegetation from stream banks, reductions in the amount of groundwater input to streams, construction of lakes and ponds, increased stormwater runoff to streams, and micro-climate changes associated with increased levels of impervious surfaces such as streets, parking lots, and roof tops (Klein, 1979; Pluhowski, 1970).

The following sections examine in varying detail the general influence of watershed urbanization, riparian cover, stream order and stormwater management BMP's on the temperature of small, headwater streams (stream order 1 - 3).

1. Influence of Watershed Imperviousness

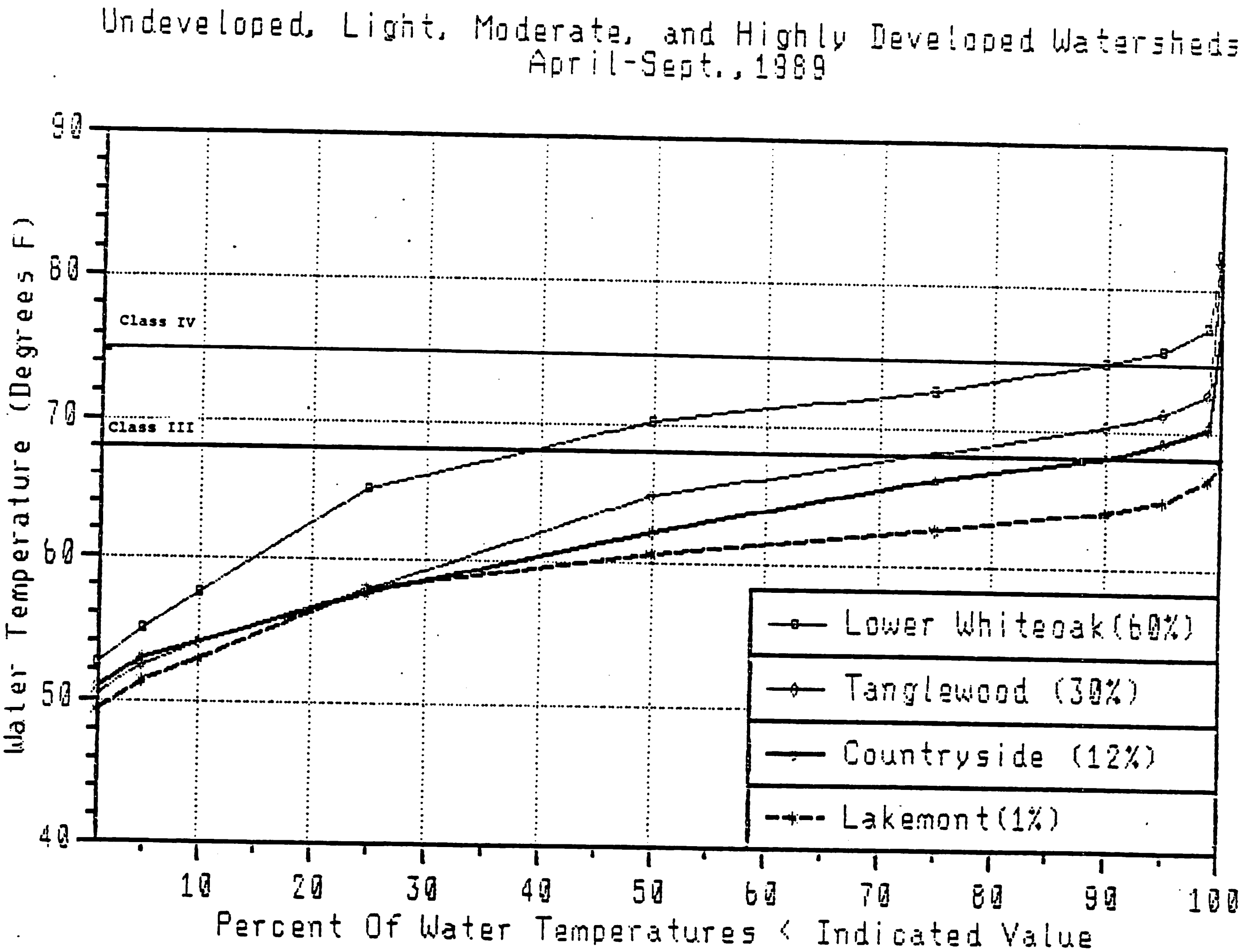
The water temperature of small, heavily shaded, free-flowing Piedmont streams generally increases with increasing percentages of watershed imperviousness. As seen in Figure 6, no violation of MDE Class I, III, or IV temperature standards occurred at the undeveloped Lakemont station during the course of this study. However, both the frequency and magnitude of Class III and IV violations increased directly with corresponding increases in watershed imperviousness. Figure 6 also provides several other interesting insights into the relationship between imperviousness and stream temperature.

- The consistently cold water temperatures reported at the undeveloped Lakemont tributary station strongly suggest that, from a historical perspective, most headwater Piedmont streams in Maryland were once cold enough to support naturally reproducing trout populations and/or their associated support organisms.

- The impact of watershed development on stream temperatures was still evident in lightly developed watersheds. Even at the relatively low 12 percent watershed imperviousness level (Countryside inflow station), neither MDE Class III or IV temperature standards could be met 100 percent of the time (Class III and IV violations occurred 10 and 1 percent of the time, respectively). As previously noted, the frequency and magnitude of Class III and IV violations rose steadily with associated increases in the level of imperviousness. For

FIGURE 6

UNDEVELOPED VERSUS URBAN STREAM TEMPERATURES



example, at the moderately developed, 30 percent impervious Tanglewood inflow station the frequency of Class III and IV violations occurred 25 and 1 percent of the time, respectively. However, at the heavily developed 60 percent impervious level (Lower White Oak tributary) Class III and IV standards were violated 60 and 10 percent of the time, respectively. The preceding findings bolster Klein's (1979) contention that sensitive coldwater fish, such as trout, may be negatively affected when watershed imperviousness exceeds 10 percent.

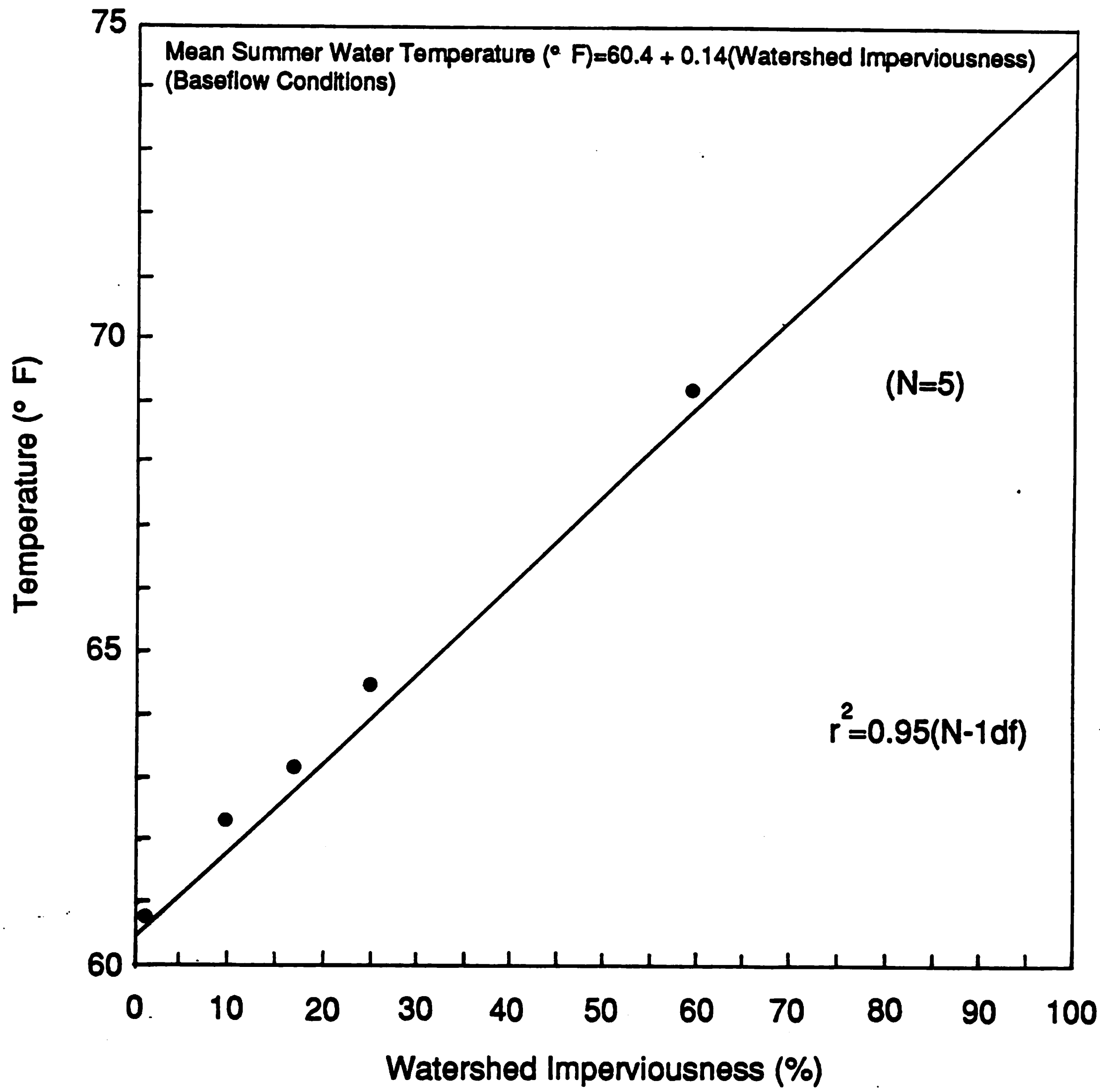
- Only about one percent of all recorded water temperatures at the Tanglewood inflow and Lower White Oak stations equalled or exceeded 80°F. Although representing only a very small percentage of all recorded temperatures, these temperatures are significant in that they exceed the temperature tolerance of most coldwater organisms.

- No violation of the 90°F MDE Class I water temperature standard was reported, at any stations during the study. However, a recently completed study of the urban Anacostia River basin (Kumble, 1990) indicates that this temperature standard is frequently violated by large streams during summer months.

Further analysis of the data revealed a strong linear relationship between mean late spring-summer water temperatures and watershed imperviousness. As seen in Figure 7, an estimate of the mean, late spring-summer water temperature of small, heavily shaded, headwater Piedmont streams was derived from the following equation:

FIGURE 7

RELATIONSHIP BETWEEN WATERSHED IMPERVIOUSNESS AND WATER TEMPERATURE



Mean Water Temperature (^{o}F) = 60.4 + 0.136 (percent watershed imperviousness)

This least squares linear regression yields a correlation coefficient (r2), adjusted for degrees of freedom, of 0.95; indicating a strong general relationship between water temperature and watershed imperviousness.

The preceding equation indicates that for each one percent increase in watershed imperviousness there is a corresponding stream Delta-T increase of about 0.14^{o}F. It is further noted that this equation pertains to streams in the study area under a slightly cooler than normal air temperature scenario.

Results supported the findings of Pluhowski (1970) that urbanization can markedly increase the average summer temperature of small streams. For example, closer examination of the Lower White Oak versus Lakemont water temperature distributions (Figure 8) revealed that Lower White Oak was typically 4 - 15 ^{o}F warmer than the undeveloped, forested Lakemont tributary. The average Delta-T increase for this highly urbanized stream was 8.6 ^{o}F. Maximum daily instantaneous water temperatures at the Lower White Oak station reached a high of 82.6^{o}F. This represented the highest recorded free-flowing stream temperature in the study. In contrast, the highest maximum daily instantaneous water temperature at the Lakemont station was 67.8^{o}F.

As expected, maximum daily water temperatures for all monitoring stations were recorded in July and August, the warmest months during the study. Figure 9, provides an interesting examination of the relationship between

FIGURE 8

COMPARISON OF UNDEVELOPED VERSUS HIGHLY DEVELOPED STREAM TEMPERATURES

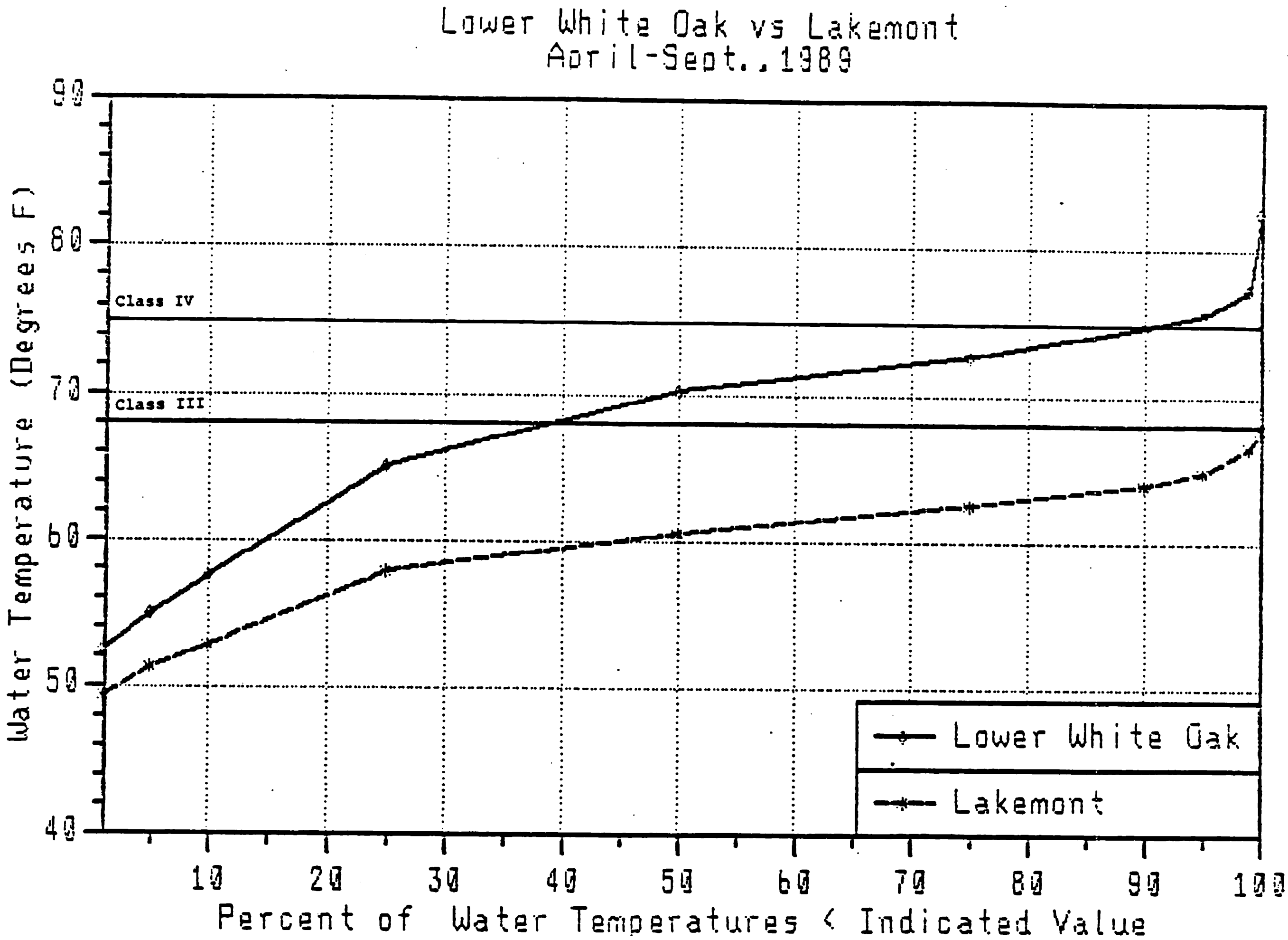
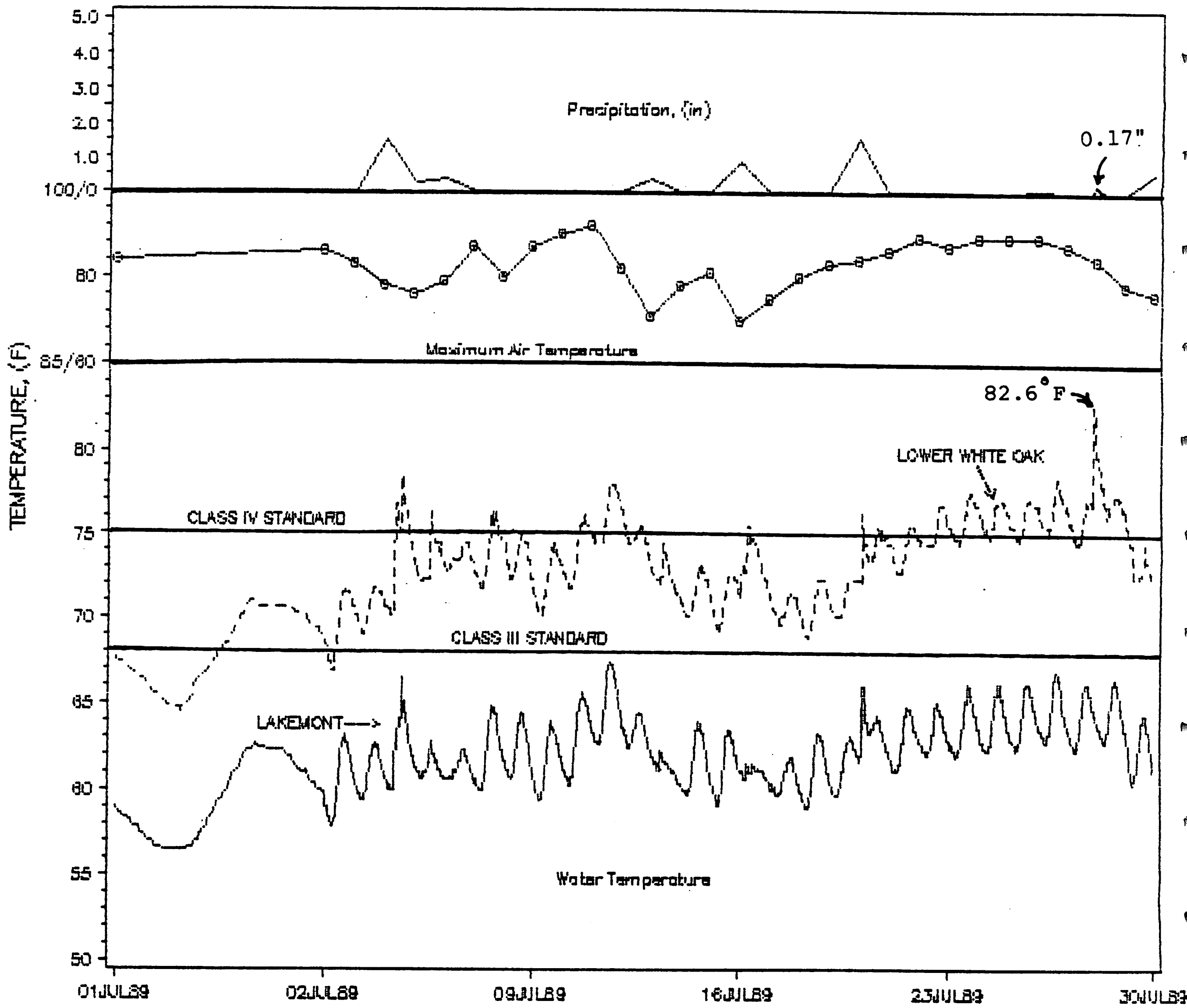


FIGURE 9

GENERAL RELATIONSHIP BETWEEN MAXIMUM AIR TEMPERATURE, PRECIPITATION AND UNDEVELOPED AND HIGHLY DEVELOPED STREAM TEMPERATURES



water temperature and climatological conditions at the Lakemont and Lower White Oak stations during the July period. Major findings are as follows:

- Both sites exhibited similar daily (or diurnal) stream Delta-T temperature fluctuations of between 2 and 8^{O}F. The daily range in water temperatures generally followed the late afternoon (maximum) and early morning (minimum) pattern common to most North American streams.

- High maximum daily Delta-T stream temperatures at both stations, corresponded closely to periods of high maximum daily air temperatures. MDE Class IV temperature standard violations at the lower White Oak tributary occurred on a regular basis during periods of sustained high air temperature (i.e., air temperatures $\geq$ 85 ^{O}F). Water temperatures in the mid to upper 70's were common at the White Oak tributary station during these high air temperature periods.

- In general,the stream temperatures were more responsive to daily air temperature fluctuations than to rainfall-runoff events.

- Approximately one percent of all storms produced major daily Delta-T increases at the heavily developed White Oak tributary. The highest water temperature recorded at this site (82.6^{O}F) was the result of a brief, intense local shower which dropped 0.17 inches of rain. Delta-T stream temperatures responded to the influx of warm stormwater runoff by increasing 5.8^{O}F in 20 minutes (Figure 9).

Interestingly, the maximum instantaneous water temperature of 82.6°F was reached at 10:00 p.m. (some 35 minutes after the start of the storm).

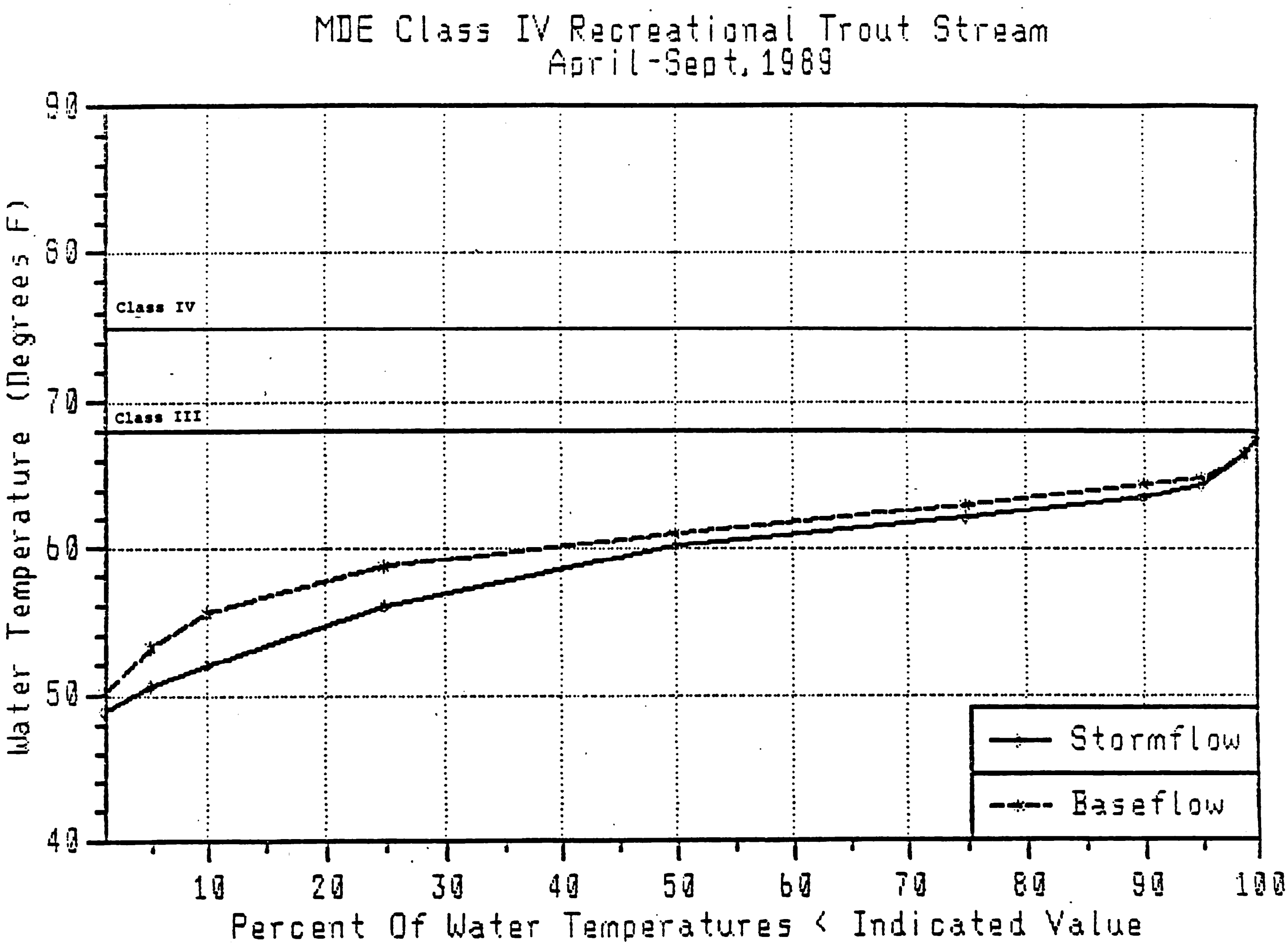
2. Baseflow versus Stormflow Conditions

In order to determine what general effect(s) rainfall-runoff events had on free-flowing streams draining watershed areas of different background levels of imperviousness, a series of simplified baseflow versus stormflow plots were made for the Lakemont, Countryside inflow, Tanglewood inflow, and Lower White Oak stations. For the purposes of the study, baseflow conditions were simply defined as dates in which no rainfall fell at the Glenmont, MD weather station. All other non-baseflow dates were considered to be, to some extent, under the varying influence of stormflow conditions (i.e., precipitation, cooler air temperatures, and/or increased cloud cover). Stormflow days were further defined as dates in which $\geq$ 0.01 inches of precipitation fell at the Glenmont, MD station. During the study, stormflow and baseflow dates respectively comprised 48.5 and 51.5 percent of the record. Results from this portion of the study are graphically presented as Figures 10 - 13. Major findings are summarized below:

- During the entire study period, baseflow and stormflow water temperatures in the undeveloped watershed (Figure 10) were within four degrees Fahrenheit of one another. Stormflow water temperatures never exceeded baseflow temperatures, and in fact were cooler approximately 95 percent of the time. This finding strongly suggests that the increased cloud cover and cooler air temperatures associated with most rainy day - stormflow conditions generally depress the water temperature of small, heavily-shaded headwater streams. In addition, an increase in groundwater inflow, from

FIGURE 10

EFFECT OF STORMFLOW ON UNDEVELOPED LAKEMONT TRIBUTARY STREAM TEMPERATURES



infiltration of rainfall, may also contribute to overall stream temperature reduction.

- Results from both the lightly developed watershed (12 percent impervious) and moderately developed (30 percent impervious) watersheds stations were generally similar to those from the undeveloped Lakemont tributary. Countryside stormflow temperatures (Figure 11) were cooler than baseflow temperatures approximately 94 percent of the time. As seen in Figure 11, approximately 5 percent of the stormflow temperatures at this ightly developed watershed site exceeded the 68°F Class III stand t; whereas, only 1 percent exceeded the 75°F Class IV standard n contrast, Countryside baseflow temperatures exceeded the Clas and IV standards 10 and 0 percent of the time, respectively. e moderately developed Tanglewood site (Figure 12), bot ormflow and baseflow temperatures exceeded the Class III and andards 25 and 1 percent of the time, respectively.

- Although we expected stormflow temp es at the highly developed watershed site to be much higher t baseflow temperatures and to exhibit large temperature spikes, this was generally not the case. In fact, stormflow temperatures at the Lower White Oak station (Figure 13) were equal to or cooler than baseflow temperatures 99 percent of the time. Air temperature seemed to be a more important factor than storms, about 90 - 95 percent of the time. Under stormflow conditions, Class III and IV standards were violated 57 and 10 percent of the time, respectively. Baseflow water temperature

FIGURE 11

EFFECT OF STORMFLOW ON LIGHTLY DEVELOPED COUNTRYSIDE INFLOW STREAM TEMPERATURES

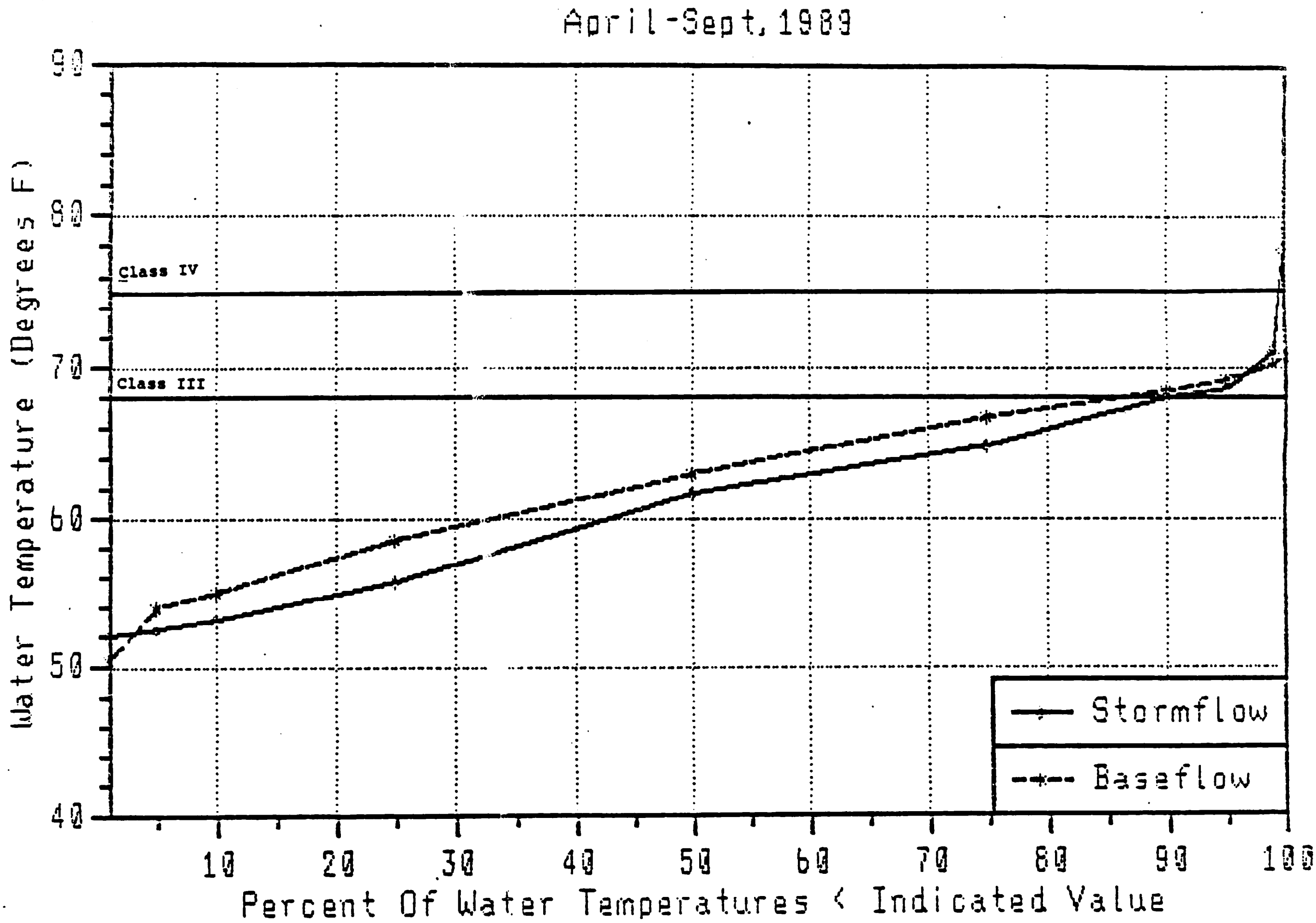


FIGURE 12

EFFECT OF STORMFLOW ON MODERATELY DEVELOPED TANGLEWOOD INFLOW STREAM TEMPERATURES

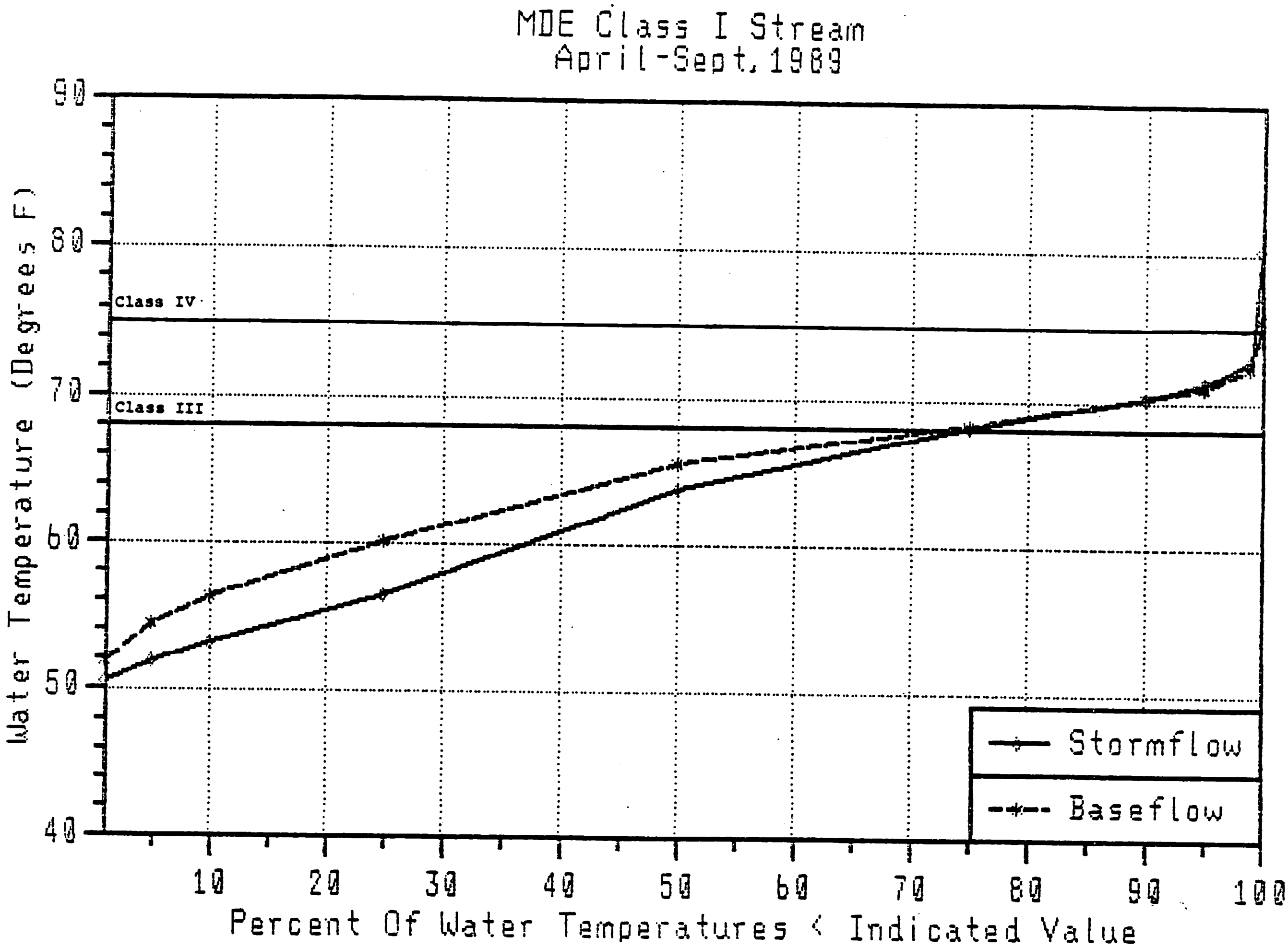
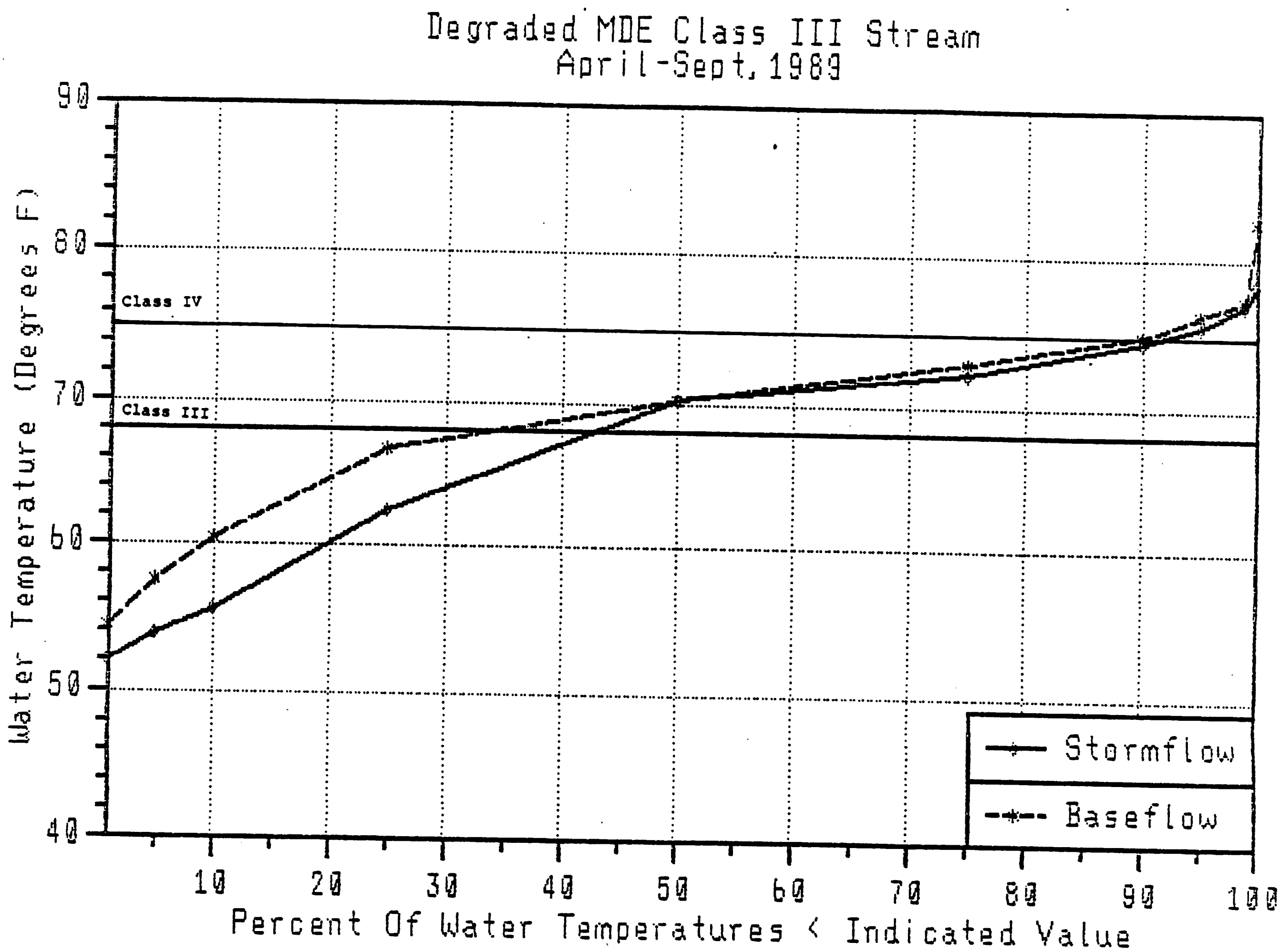


FIGURE 13

EFFECT OF STORMFLOW ON HIGHLY DEVELOPED LOWER WHITE OAK STREAM TEMPERATURES



violated the preceding standards 67 and 12 percent of the time, respectively.

In summary, results show that stormflow temperatures are generally cooler than baseflow temperatures. However, in developed watersheds stormflow temperatures will be higher, roughly 1-5 percent of the time, when certain conditions are met. The three principal conditions are:

1. The storm event occurs during a high air temperature period, or date;

2. Precipitation occurs mainly as the result of heavy shower activity; and

3. The amount of precipitation is sufficient to generate significant runoff. In highly developed watersheds the amount of rainfall needed to generate significant volumes of runoff can be as little as 0.1 inches.

The preceding conditions or factors explain the rapid, "J-"shaped curve increase evident in the upper right hand corner of the plots for the developed watersheds (Figures 11, 12, and 13). They do not, however, adequately explain the flatter temperature curve response observed at the Lakemont site (Figure 10).

3. Role of Riparian Vegetation

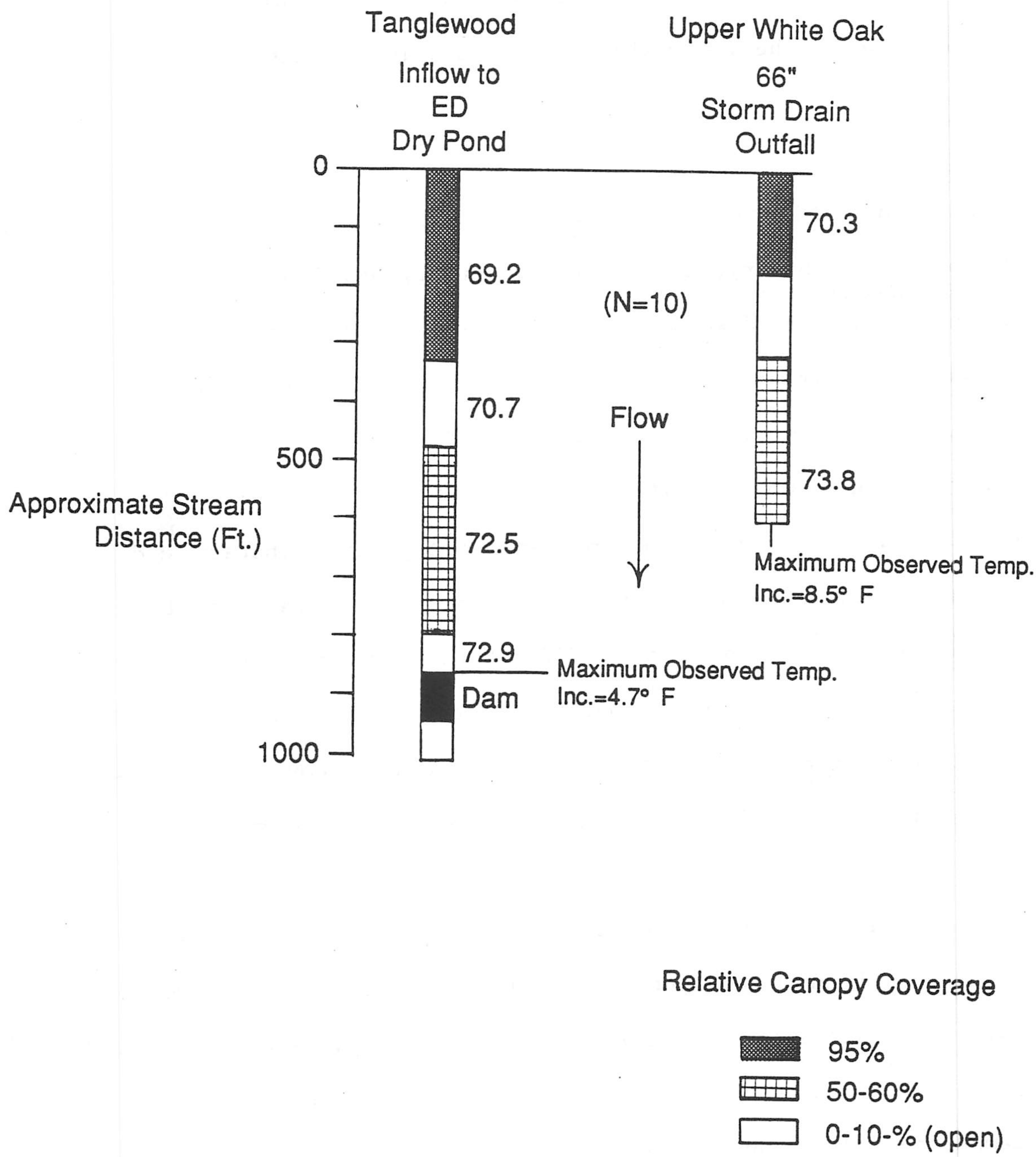
Studies have shown that the partial and/or complete removal of stream-side vegetation can raise summer stream temperatures by as much as 11 - 20^{o}F and can reduce winter water temperatures by up to 5 - 7 ^{o}F (Gray and Edington, 1969; Hewlett and Forston, 1982; Lynch et al., 1980). The importance of riparian vegetation as a thermal insulator of small, headwater streams cannot be overemphasized. In particular, during summer months, an umbrella of dense vegetation typically shields natural streams from solar radiation; thereby reducing daily temperature fluctuations. Unfortunately, the common practice of removing riparian vegetation can greatly alter the temperature regime of small streams. Even relatively short open, or partially shaded stream reaches can produce a major elevation of downstream water temperatures.

Limited instantaneous grab sampling results from both the White Oak and Tanglewood tributaries revealed a maximum stream Delta-T increase of 8.5^{o}F after the streams flowed through 150 foot long unshaded reaches (Figure 14). On average, a Delta-T increase of 3.5 - 3.7^{o}F occurred when water flowed through relatively short (approximately 150 - 300 feet long), open or partially-shaded stream reaches. Although stream depth, current velocities, and discharge were comparable in both tributaries, the White Oak tributary had the highest observed temperature increase.

Physical factors such as stream channel width, depth of flow, current velocity, and volume of flow are known to play key roles in determining to what extent exposed stream reaches will be warmed by increased solar

Figure 14

Influence of Canopy Coverage on Mean Baseflow Temperature (° F) 1/
June-August, 1989



1/-The mean baseflow for Tanglewood & Upper White Oak during this period was 0.26 and 0.35 cfs, respectively.

radiation. In general, the smaller the discharge, and the greater the amount of exposed stream surface area and travel time, the higher the potential temperature increase. Given that the 12 foot wide White Oak tributary is 2 to 3 times wider than the Tanglewood tributary, it appears that the greater amount of exposed surface area per unit volume of flow was primarily responsible for the observed higher temperature increases.

As seen in Figure 15, once elevated by the addition of warm water from the Oaksprings tributary, Gum Springs tributary baseflow temperatures did not demonstrably cool-down within the 1200 foot long test reach. In fact, temperatures remained elevated all the way downstream to the confluence with Paint Branch (a distance of approximately 1900 feet). While initially experiencing a stream Delta-T increase of 11.4^{O}F after flowing through the Countryside wet pond, the smaller Countryside tributary did cool down slightly over a similar distance. However, the stream still posted a net stream Delta-T increase of 8.3^{O}F. Since both test stream reaches were heavily shaded and air temperature along each respective tributary was constant, factors other than riparian canopy coverage apparently were responsible for the 3.1^{O}F cooling-effect observed at the Countryside site.

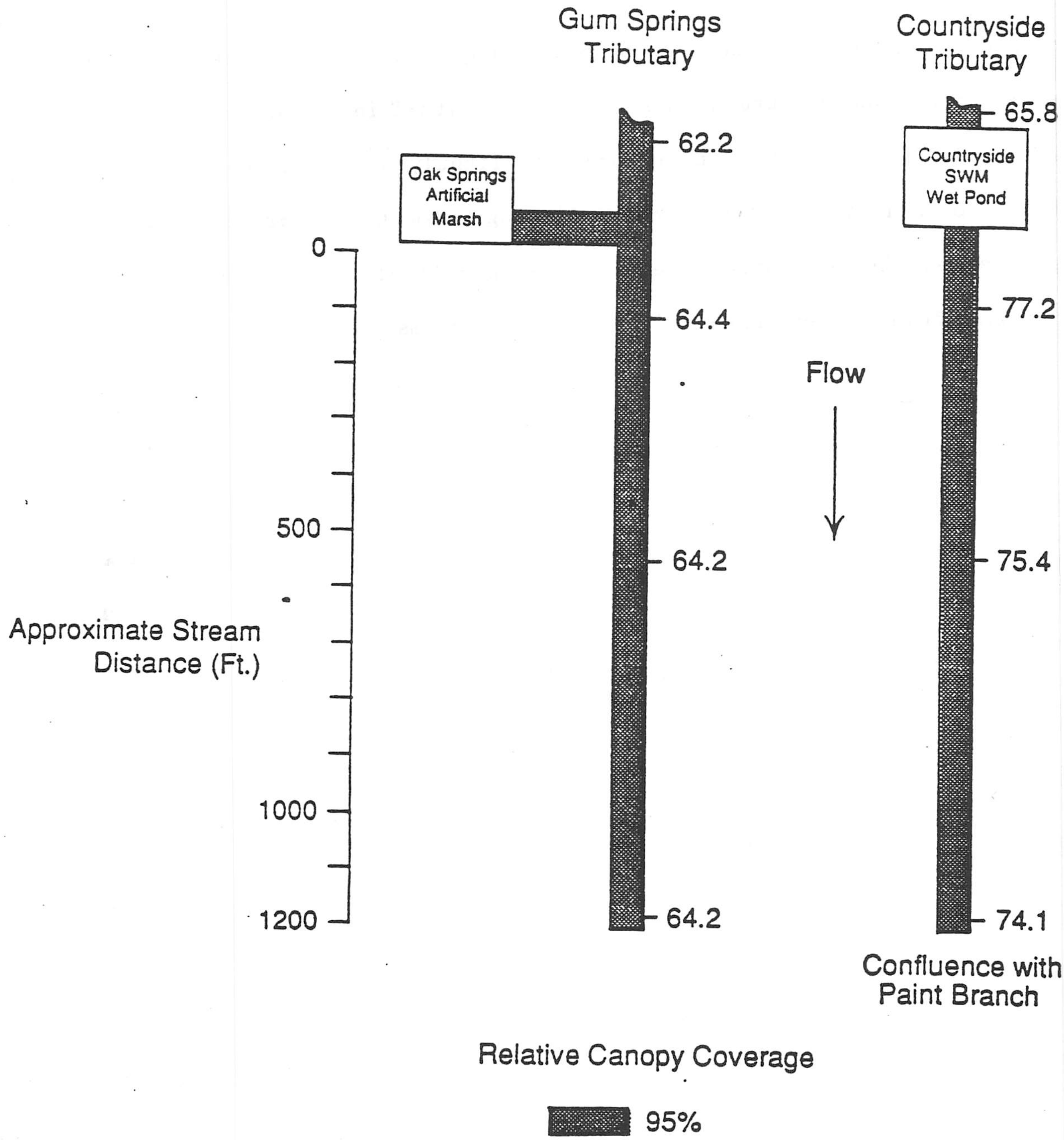
Research has demonstrated that the temperature of small streams can be significantly reduced upon passage through heavily shaded reaches (Klein, 1979; Karr and Schlosser, 1977). However, it is widely acknowledged that as stream flow increases, the influence of riparian vegetation on stream temperature decreases. Once warmed, considerable energy must be expended to cool-down streams. Whether or not the small observed decrease in Countryside

FIGURE 15

RELATIONSHIP BETWEEN CANOPY COVERAGE AND STREAM SIZE ON MEAN WATER TEMPERATURE

June-August, 1989 Baseflow Conditions[1/]

(N=10)



1/-The mean baseflow for Countryside & Gum Springs during this period was 0.25 and 0.99 cfs, respectively.

water temperature was attributable to the influence of groundwater inputs, greater conduction of heat to the streambed and banks, higher convection rates, or some other means of thermal energy reduction remains unclear.

The preceding results show that on hot, sunny days the water temperature of small, poorly shaded streams can experience Delta-T increases on the order of 1.0 - 3.0°F per 100 feet of open or lightly-shaded channel length. Results also indicated that even after flowing through 1000 or more feet of forested stream buffer, stream temperatures are likely to remain elevated. This is particularly the case for larger-sized streams.

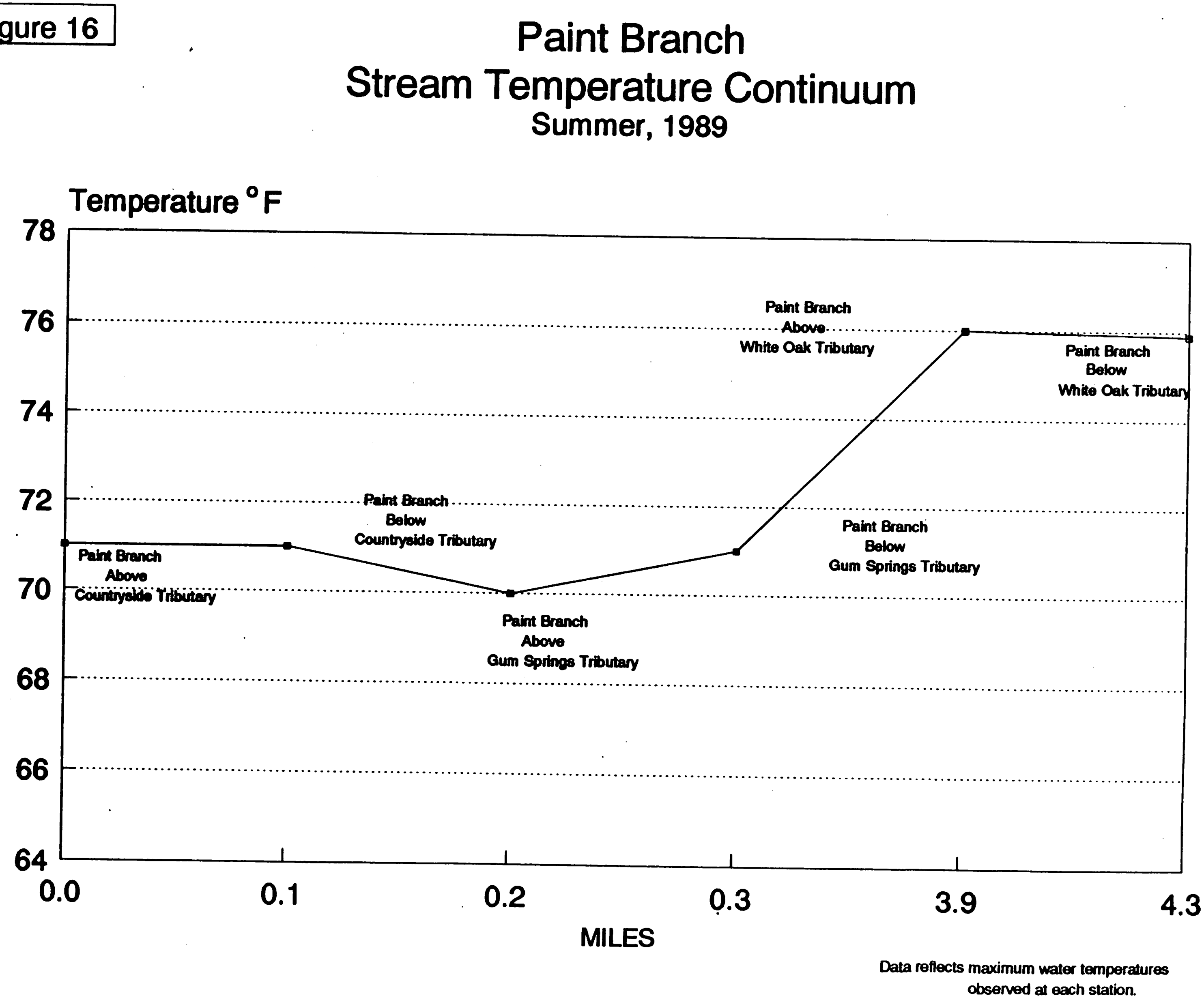
4. Stream Temperature As a Function of Stream Order

Macan (1958) reported that the temperature of small headwater streams warmed up and reached equilibrium within relatively short distances from their source. This is primarily attributed to the response of small streams to both air temperature variations and riparian canopy coverage. In addition, stream temperatures generally increase in a downstream direction with increasing stream order and/or distance from the source.

The premise that a temperature continuum normally exists within urban stream systems is supported by findings from the grab sampling portion of the study. As illustrated in Figure 16, stream temperatures along the mainstem of Paint Branch (a third-order stream) increased in a downstream direction. Over the course of approximately 4.3 stream miles, an average mainstem stream Delta-T increase of 5.0°F occurred. However, when compared to cooler first-order tributary areas such as the Upper Gum Springs, the average Lower Paint Branch increase was actually 14.0°F.

The observed 14.0°F stream continuum temperature increase, which represents the "watershed Delta-T effect," is the result of a combination of natural phenomena and anthropogenic factors. In the case of the urban Paint Branch, the watershed's Delta-T effect produces a 1.0 - 2.0°F baseflow temperature increase per stream mile. Results further suggest that smaller, low-order urban streams are most sensitive to this watershed Delta-T effect.

Figure 16


Paint Branch
Stream Temperature Continuum
Summer, 1989
Temperature °F
78
76
74
72
70
68
66
64
0.0
0.1
0.2
0.3
3.9
4.3
MILES
Paint Branch Above Countryside Tributary
Paint Branch Below Countryside Tributary
Paint Branch Above Gum Springs Tributary
Paint Branch Below Gum Springs Tributary
Paint Branch Above White Oak Tributary
Paint Branch Below White Oak Tributary
Data reflects maximum water temperatures observed at each station.

5. Effect of Stormwater Management BMP's on Water Temperature Distribution: MDE Water Temperature Standard Performance Series

None of the four urban BMP sites were thermally neutral. While no violation of MDE Class I temperature standards were recorded during the study, outflow from all four of the monitored stormwater management BMP sites violated either Class III or IV standards some of the time. As seen in Figure 17, the Fairland Ridge infiltration - dry pond facility had the lowest recorded BMP outflow temperatures. This hybrid BMP site violated Class III and IV standards 8 and 1 percent of the time, respectively. The highest outflow station temperatures were recorded at the Countryside wet pond. This BMP violated Class III and IV standards 75 and 50 percent of the time, respectively. Temperatures at the Countryside pond outflow station were, in comparison to the other three BMP sites, higher 75 percent of the time. Major findings are presented below. In addition, the BMP Delta-T performance for each site is summarized in Table 5 and described in greater detail in the following sections.

- All four BMP's increased receiving stream temperatures during baseflow conditions. The average BMP baseflow Delta-T increase ranged from a low of 2.6^{o}F at the infiltration-dry pond site, to a high of 9.7^{o}F at the wet pond (Table 5).

- During stormflow conditions, all four BMP's raised downstream water temperatures. Once again, the infiltration-dry pond produced the

FIGURE 17

COMPARISON OF STORMWATER MANAGEMENT BMP OUTFLOW TEMPERATURES: INFILTRATION-DRY POND, ARTIFICIAL WETLAND, EXTENDED DETENTION DRY POND AND WET POND

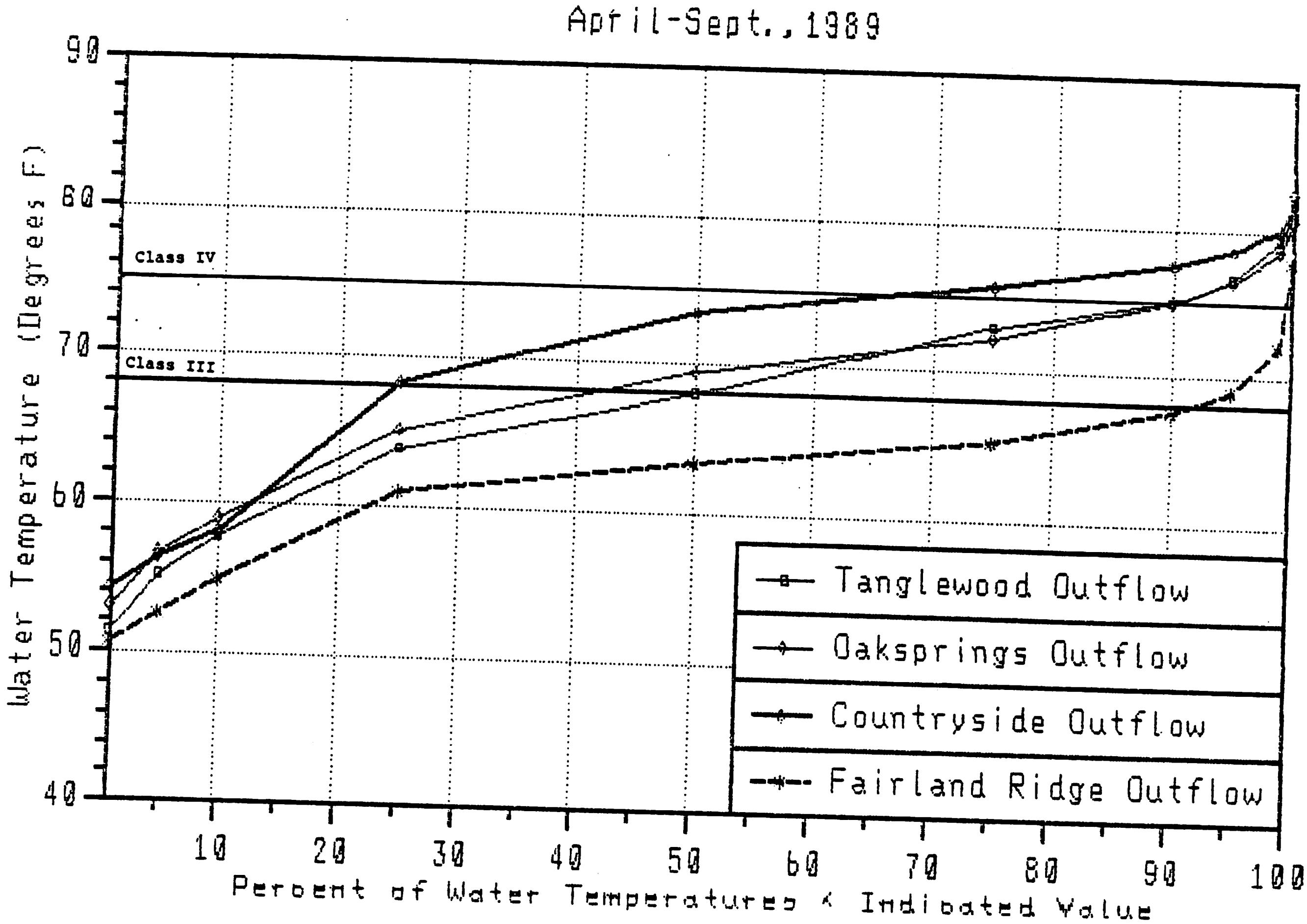


Table 5. Summary: Stream and BMP Delta-T Temperatures (°F)

	Location	Representative Type	Baseflow Max.	Baseflow Avg.	Stormflow Max.	Stormflow Avg.	Total (Base & Stormflow) Max.	Total (Base & Stormflow) Avg.
STREAM	Countryside Inflow	Lightly Developed Watershed (12% impervious)	6.5	1.9	9.4	2.0	9.4	1.9
STREAM	Tanglewood Inflow	Moderately Developed Watershed (30% impervious)	14.0	5.0	16.1	5.2	15.0	5.1
STREAM	Lower White Oak	Highly Developed Watershed (60% impervious)	16.2	8.7	15.5	8.5	16.2	8.6
BMP	Fairland Ridge	Infiltration-Dry Pond	7.6	2.6	5.0	2.3	7.6	2.5
BMP	Oaksprings	ED Wetland	8.7	3.9	7.8	2.4	8.7	3.2
BMP	TangleWood	ED Dry Pond	9.7	5.5	11.2	5.2	10.9	5.3
BMP	Countryside	Wet Pond	15.1	9.7	14.0	8.5	15.1	9.1

1/ Lakemont used as reference to calculate stream Delta-T; Inflow station used as reference to calculate BMP Delta-T.

smallest average BMP Delta-T increase (2.3°F). The wet pond had the largest average Delta-T increase (8.5°F). In addition, all four BMP's raised stormflow temperatures in the "J" section of the temperature curve.

- BMP Delta-T's were sufficient to dramatically increase the frequency and magnitude of temperature standards violations, and in some cases, were high enough to have severely impacted downstream coldwater organisms (had they been present).

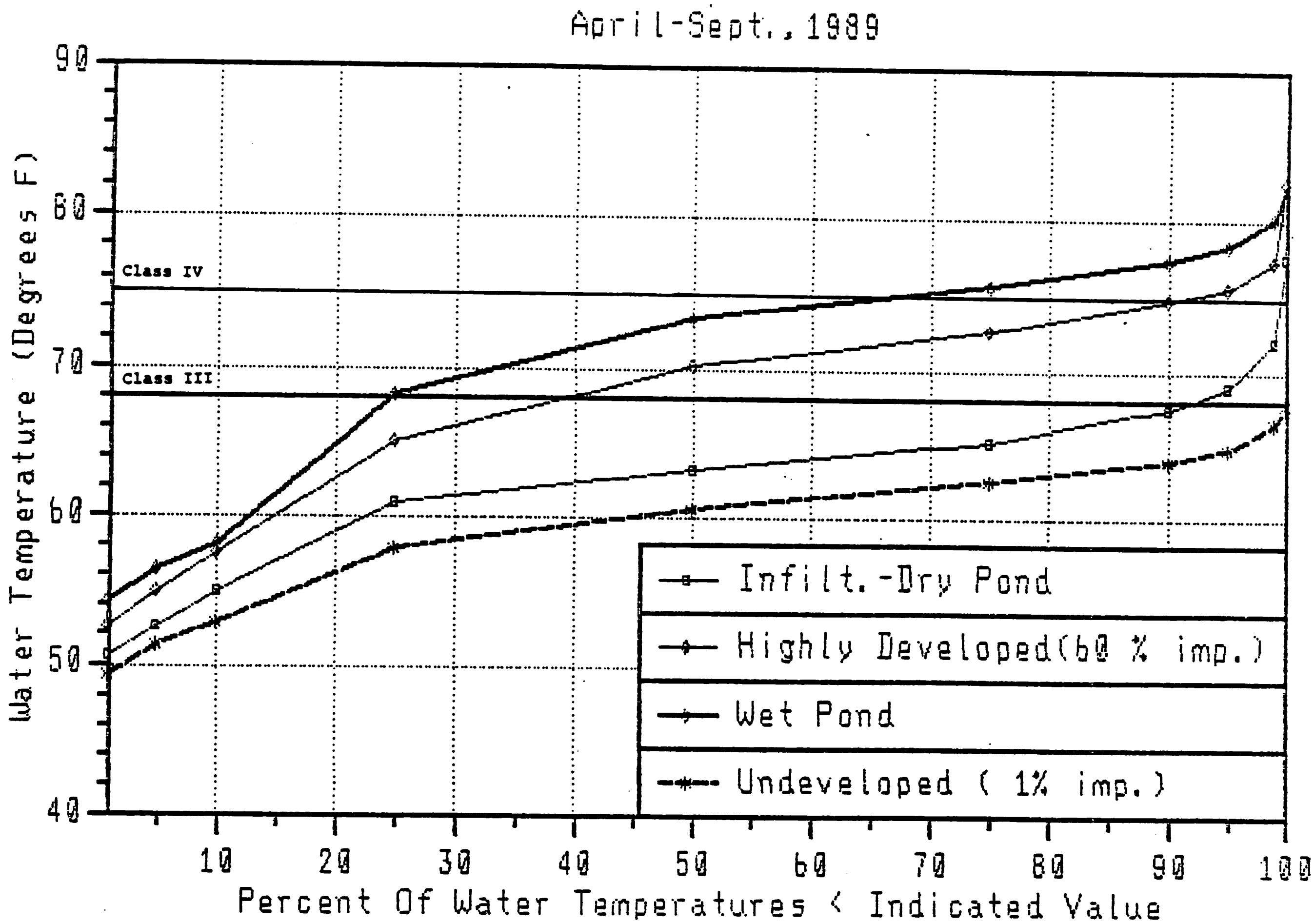
- Outflow from the Tanglewood extended detention (ED) dry pond violated Class III and IV temperatures standards 80 and 10 percent of the time, respectively. This station had the highest percentage of Class III violations recorded (by any station) in the entire study.

- The Oaksprings ED wetland outflow station violated Class III and IV standards 58 and 10 percent of the time, respectively.

Figure 18 provides additional comparative information on the influence of both stormwater management BMP's and background levels of watershed imperviousness on receiving stream temperatures. Not surprisingly, high levels of watershed imperviousness and/or introduction of BMP's into headwater stream areas can produce average total stream Delta-T increases of 2.5 - 9.1°F. Closer examination of the data indicated that the average total stream Delta-T increase was 9.1°F for the wet pond, versus 8.6°F for the highly developed watershed. In addition, both scenarios reported identical maximum instantaneous stream temperatures of 82.6°F. As seen in Table 5, the

FIGURE 18

COMPARITIVE THERMAL IMPACTS OF URBANIZATION AND STORMWATER MANAGEMENT BMP'S: UNDEVELOPED, HIGHLY DEVELOPED, INFILTRATION-DRY POND AND WET POND

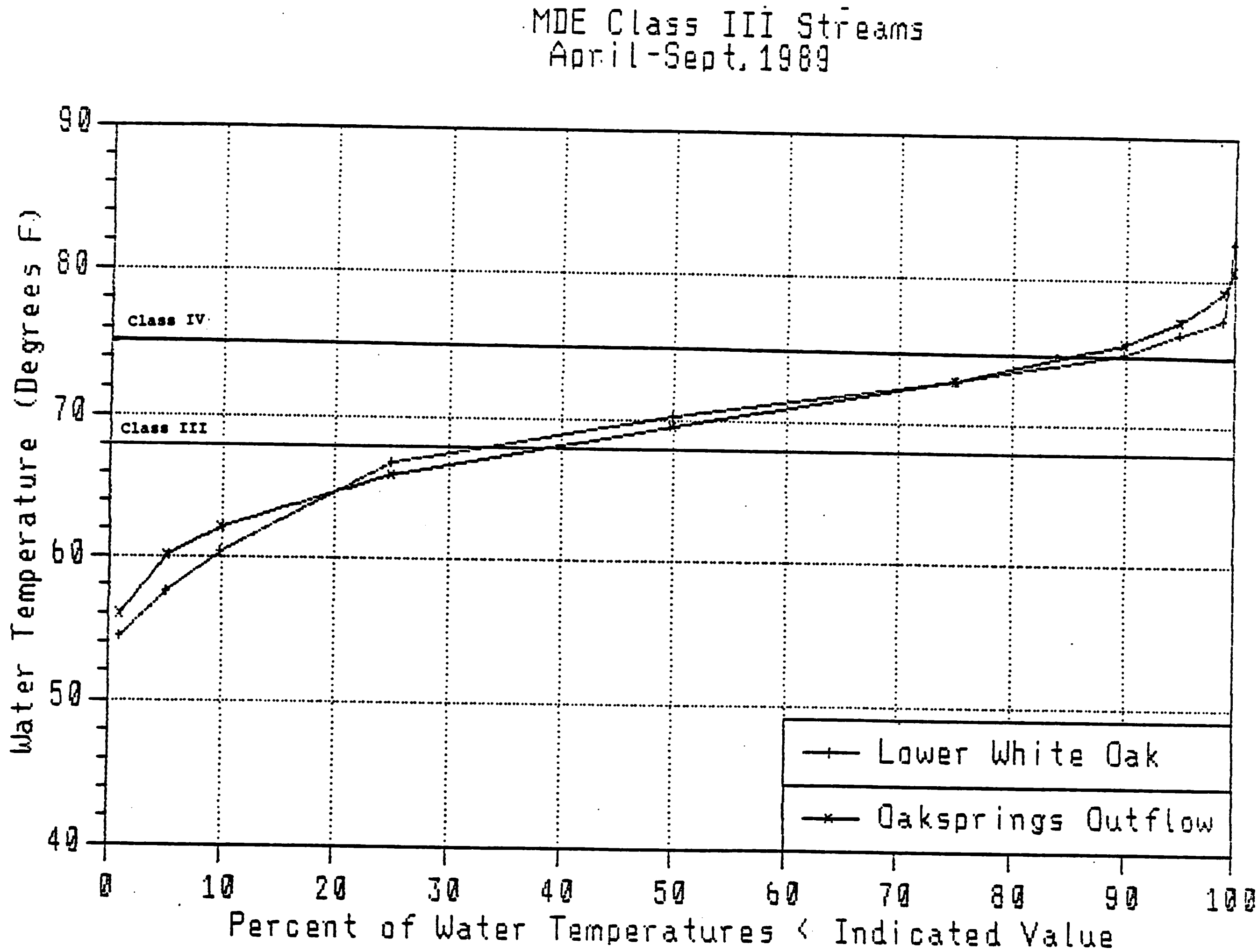


highly developed watershed produced an average total Delta-T increase which was 6.1°F higher than the infiltration - dry pond BMP.

A comparison of both the highly developed watershed and ED wetland outflow stream temperatures (Figure 19) reveals that the thermal regime of the two sites are virtually identical. The preceding results provide compelling evidence that at high levels of watershed imperviousness, the thermal impacts to the receiving stream system closely resemble those produced by wet and/or extended detention stormwater management BMP's.

FIGURE 19

COMPARISON OF HIGHLY DEVELOPED AND ARTIFICIAL WETLAND OUTFLOW STREAM TEMPERATURES



Summary

Results from the study indicate that the temperature regime of small, urban headwater streams is greatly influenced by the five following factors:

1. Degree of watershed urbanization. Imperviousness, together with local meteorological conditions, generally had the largest influence on urban stream temperatures. Results from the study indicate that the average water temperature of urban streams increases on the order of $0.14^{o}F$ per one percent increase in watershed imperviousness. When compared against the undeveloped watershed, the average total stream Delta-T increase at the 12 percent impervious watershed was $1.9^{o}F$, versus $8.6^{o}F$ at the 60 percent impervious one. In addition, a general inverse relationship exists between watershed imperviousness and storm-size needed to produce large, rapid stream temperature increases.

2. Meteorological conditions. During the study the observation was made that air temperature was a more important factor than storms approximately 90 - 95 percent of the time. It was further noted that forested, undeveloped headwater streams such as the Lakemont tributary generally respond to storm events by becoming slightly cooler. This is largely due to the drop in air temperatures which accompanies most rainfall events. While this is also normally true of small urban streams, as the level of watershed imperviousness increases these streams become progressively more responsive to

inputs of stormwater runoff. In addition, the potential for large stream temperature increases is greatest during prolonged, hot weather periods which include heavy shower activity.

3. Riparian canopy coverage. Riparian vegetation plays a key role in insulating small streams from the warming effect of solar radiation. Results show that stream Delta-T's can increase an additional 1 - 3°F per 100 feet of flow through either open or poorly-shaded stream reaches.

4. Stream order. It is well known that stream temperature naturally increases in a downstream direction with increasing stream order/distance from the source. In urban watersheds a variety of anthropogenic factors, such as the removal of riparian vegetation, micro-climate changes, and reduction of groundwater inflow, add to the so-called "watershed Delta-T" effect. Monitoring results indicate that the watershed Delta-T effect for the urban, third order, Paint Branch stream system is on the order of 1 - 2 °F per stream mile. In addition, lower-order urban streams are, because of their generally smaller volume of flow, more sensitive to this background watershed effect.

5. Urban BMP's. As previously noted, all four types of stormwater management practices monitored in the study imparted additional heat to the receiving stream. The average total BMP Delta-T increase ranged from 2.5°F for the infiltration - dry pond to 9.1°F for the wet pond. Out of the four BMP's studied, the wet pond produced the

highest maximum BMP Delta-T increase.

B. Factors Influencing Stormwater Management Facility Temperature Performance

From a water temperature perspective, the performance of stormwater management wet ponds, artificial marshes, ED dry ponds, and infiltration facilities is strongly influenced by a large number of interrelated variables. These factors include, but are not limited to, the following: BMP surface area, volume and mean depth of the permanent pool, release depth (which changes relative to the facility's water surface elevation), hydraulic residence time, design storm storage capacity, infiltrative capacity of underlying soils, size and frequency of storm events, type and condition of stormwater conveyance system, BMP outfall design, watershed imperviousness, and baseflow/stormflow water temperatures. While it is beyond the scope of the study to examine each of these factors, a comprehensive examination of associated water temperatures under baseflow and stormflow conditions was performed to characterize general temperature relationships and BMP performances under field conditions.

The following sections examine baseflow-stormflow water temperature relationships, BMP baseflow-stormflow Delta-T's, thermal loading as a function of flow ratio, and stormwater management design features which contribute to thermal loading.

1. Stormwater Management BMP Performance Under Baseflow and Stormflow Conditions

Fairland Ridge Infiltration - Dry Pond

Results from the preceding section demonstrated that the Fairland Ridge infiltration - dry pond Delta-T water temperatures were the lowest of the four BMP-types monitored. The general performance of this BMP under both baseflow-stormflow and inflow versus outflow conditions is shown in Figures 20 and 23. Major findings are presented below and summarized in Tables 6 and 7.

1. As previously noted, all four BMP's had positive average total Delta-T's. However, Fairland Ridge, which had an average total BMP Delta-T increase of 2.5^{o}F, produced the smallest Delta-T increase.

2. On one occasion, Fairland Ridge outflow station temperatures were actually slightly lower than inflow station temperatures. This occurred during a cool, small storm event. The unexpected result suggests the possibility of: a) higher associated stormflow conduction and/or convection rates downstream of the BMP, and/or b) an increase in groundwater inflow downstream of the facility.

3. Larger storms (i.e., $\geq$ 1.5 inches precipitation) raised downstream temperatures considerably. The lengthy detention of stormwater runoff, together with high solar radiation levels associated with the unshaded storage pool, rip-rap pilot channel and outfall areas, were co-contributors. The maximum recorded outflow temperature of this BMP site (77.7^{o}F) was attributed to the preceding factors.

4. The thermal behavior at Fairland Ridge was unique. No other BMP monitored during the study displayed such well-pronounced extended detention effects. During large storms, this facility was capable of maintaining elevated outflow station temperatures for over 48 continuous hours.

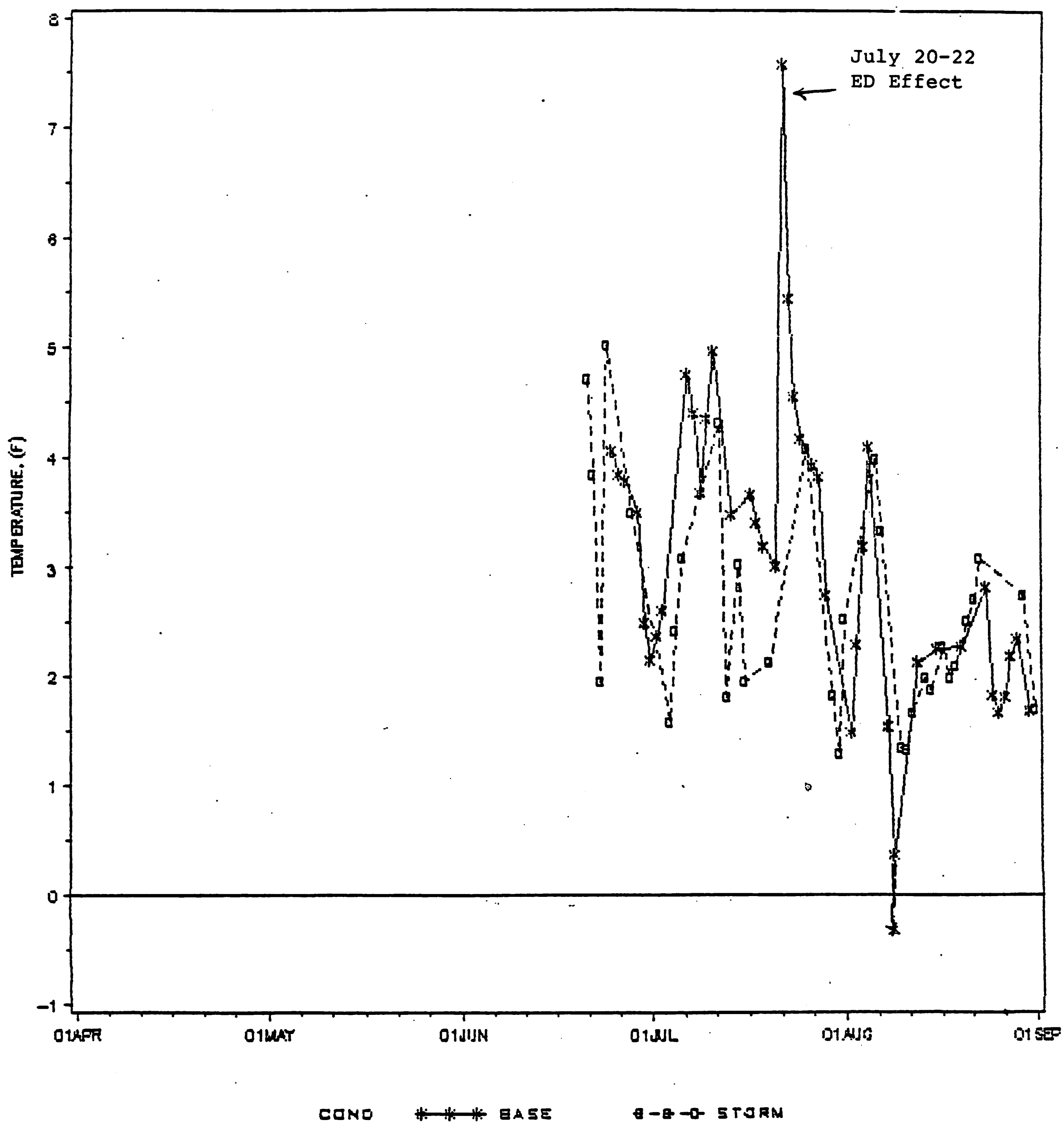
Baseflow Versus Stormflow Delta-T's

As seen in both Figure 20 and Table 6, under baseflow conditions this BMP raised outflow station temperatures an average 2.6^{o}F. It should be noted that the maximum observed Delta-T increase of 7.6^{o}F was the combined product of stormwater runoff from 1.5 inches of rainfall and the BMP facility's defacto extended detention control. Therefore, a more realistic baseflow maximum Delta-T was probably on the order of 5.0 - 6.0^{o}F.

With regard to stormflow Delta-T conditions, the infiltration dry pond raised outflow station temperatures an average 2.3^{o}F. The maximum stormflow Delta-T for this BMP was 5.0^{o}F. Approximately 65 percent of the time the

FIGURE 20

INFILTRATION-DRY POND THERMAL CHARACTERIZATION: BASEFLOW VERSUS STORMFLOW DELTA-T'S *



*Values shown are daily mean Delta-T's

Table 6 Summary: Fairland Ridge Infiltration - Dry Pond Delta-T's

Percent of Temperatures < Indicated Value	Delta-T(°F) Baseflow	Stormflow	Total
0 (minimum)	-0.3	-0.3	-0.3
1	-0.3	-0.3	-0.3
5	0.2	0.1	0.3
10	0.6	1.3	0.6
25	1.5	1.5	1.5
50 (median)	2.4	2.0	2.3
75	3.8	3.1	3.5
90	4.5	4.1	4.3
95	5.1	4.7	4.8
99	7.6	5.0	7.6
100 (maximum)	7.6	5.0	7.6

Delta-T difference between baseflow and stormflow conditions was less than 1.0°F (Table 6). Eighty-two percent of the time the positive Delta-T effect produced by this BMP was insufficient to cause a violation of the 68.0°F Class III standard. Exceedance of Class III standards was generally associated with periods of high rainfall. Only one violation of the Class IV standard was noted at this BMP site during the study.

Temperature Standard Performance

Monitoring results indicated that approximately one-fifth of all stormflow discharges from this BMP produced an increase in downstream water temperatures. They also revealed that Class III temperature standards were violated under both baseflow and stormflow scenarios, but that a 10 percent higher violation rate existed under stormflow conditions.

Under stormflow conditions (Figure 21) outflow temperatures exceeded the Class III and IV temperature standards 18 and 0 percent of the time, respectively. In contrast, baseflow outflow temperatures violated the same standards 8 and 1 percent of the time, respectively. As seen in both Figure 22 and Table 7, under stormflow conditions outflow station temperatures were slightly higher than inflow temperatures 100 percent of the time. Short, open and partially shaded reaches below this facility were primarily responsible for the slight stormflow temperature increase.

FIGURE 21

INFILTRATION-DRY POND THERMAL CHARACTERIZATION: BASEFLOW VERSUS STORMFLOW CONDITIONS

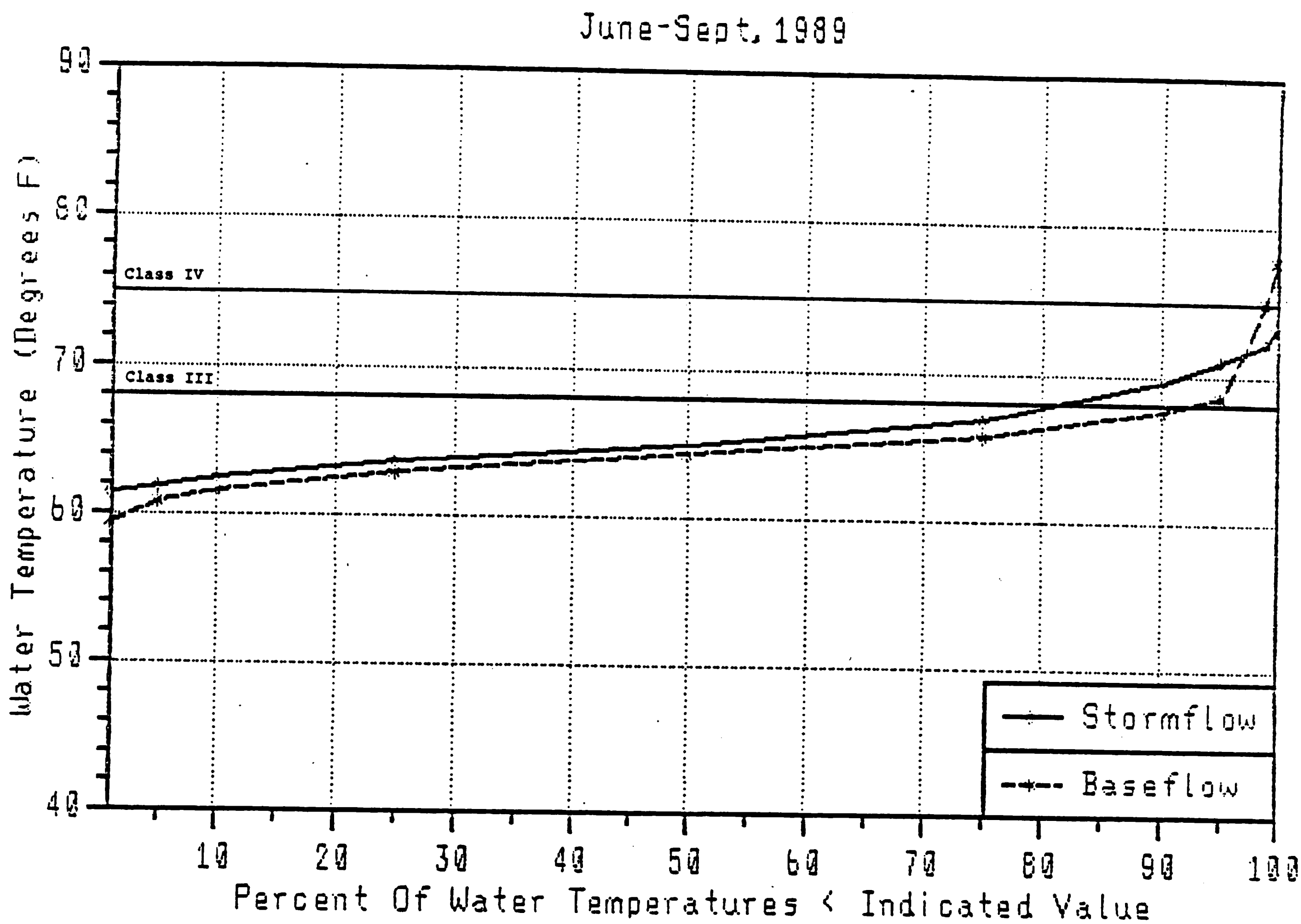


FIGURE 22

INFILTRATION-DRY POND INFLOW-OUTFLOW TEMPERATURE RELATIONSHIP DURING STORMFLOW

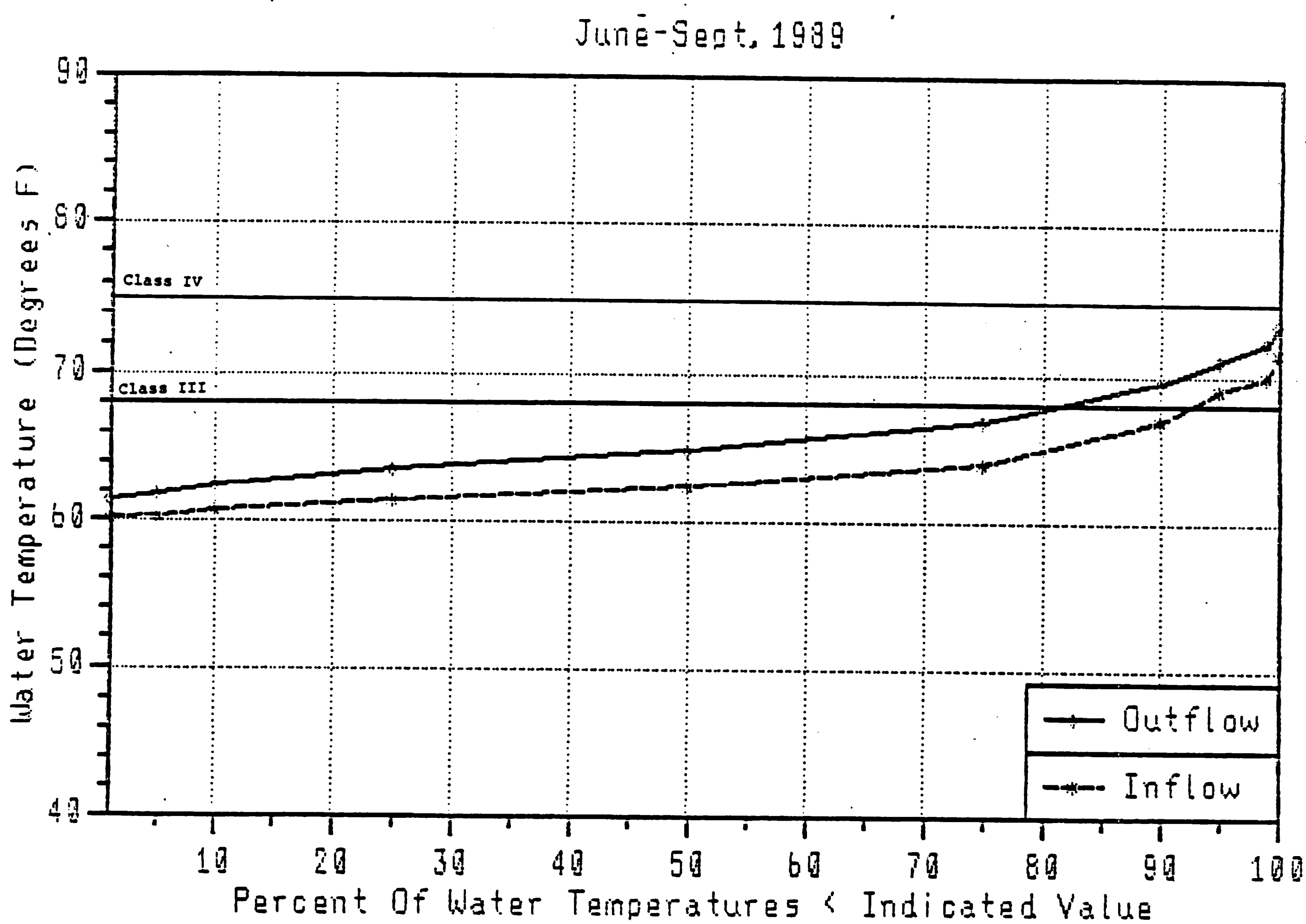


Table 7 Summary: Fairland Ridge Infiltration - Dry Pond Performance, June - Sept., 1989

Percent of Water Temperatures ≤ Indicated Value (%)	Temperature (^{o}F) Baseflow Inflow	Baseflow Outflow	Stormflow Inflow	Stormflow Outflow
0 (minimum)	58.3	59.0	59.9	61.3
1	58.6	59.5	60.1	61.5
5	59.8	60.9	60.3	61.8
10	60.3	61.6	60.7	62.4
25	61.0	62.8	61.5	63.6
50 (median)	61.7	64.3	62.4	64.8
75	62.7	65.7	64.0	66.9
90	63.2	67.5	67.0	69.6
95	63.4	68.6	68.9	71.0
99	70.5	74.9	70.0	72.3
100 (maximum)	73.8	77.7	71.5	73.4

Example of Extended Detention Effect

One of the study's more interesting findings was that the infiltration-dry pond was the only BMP observed to produce a distinct extended detention temperature effect. Although this effect occurred infrequently and was clearly associated with large precipitation events (i.e., those dropping ≥ 1.5 inches of rainfall), it resulted in markedly higher downstream water temperatures.

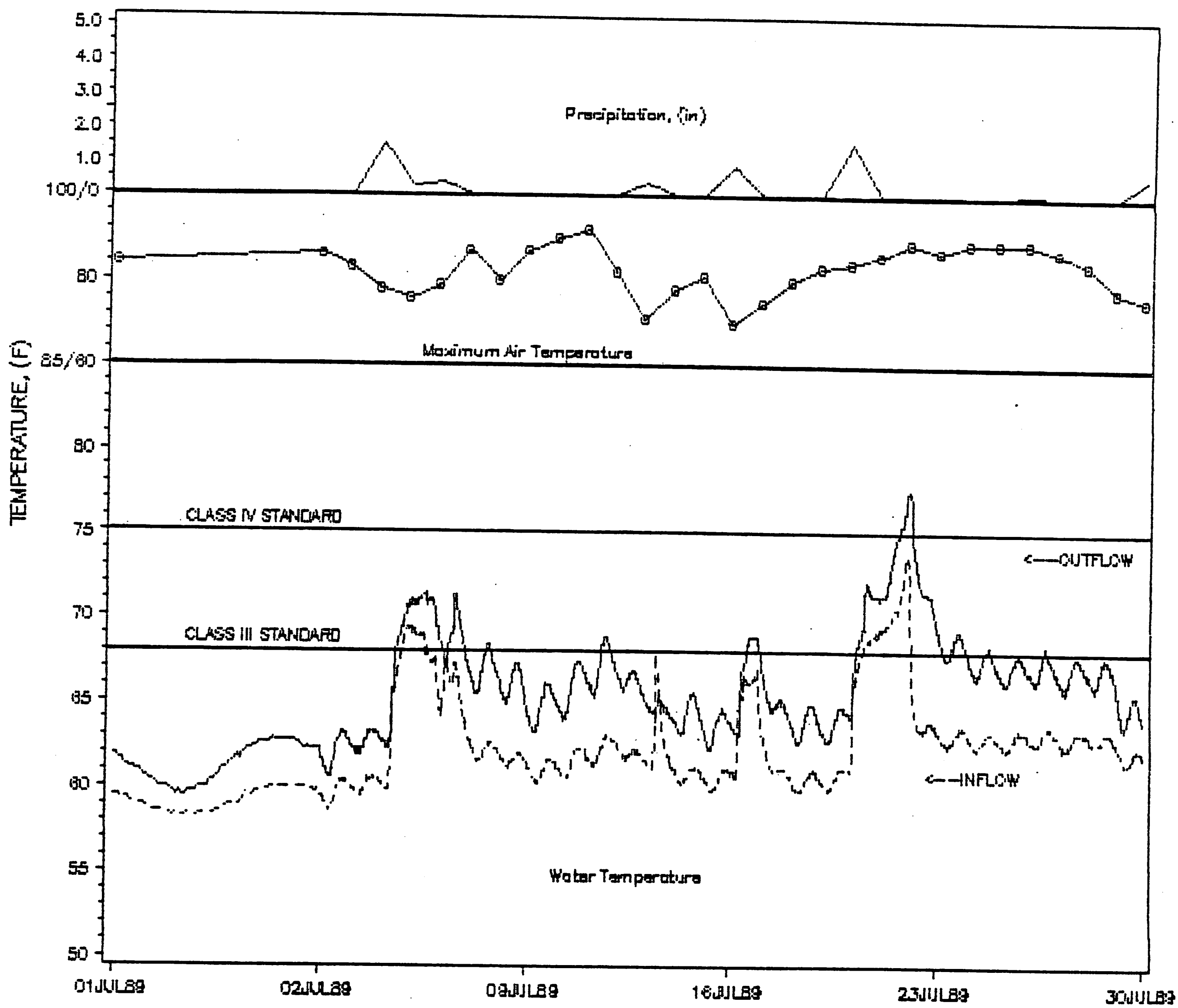
Described below is the chronology of events for the July 20, 1989 storm; which was responsible for Fairland Ridge's maximum recorded outflow station water temperature of 77.7°F.

- As seen in Figure 23, Fairland Ridge inflow-outflow temperatures rose steadily in response to the 1.5 inches of precipitation which fell between 12:30 - 5:00 a.m., July 20, 1989. Within approximately three hours after the start of the storm, both inflow and outflow station water temperatures began to rise. The increase was caused by the large influx of stormwater runoff which had overwhelmed the 0.25 inch design capacity of the infiltration trenches. By the end of the storm, several feet of runoff had been impounded in the dry pond portion of the facility.

- The facility's 8 inch diameter low flow orifice, which provided the

FIGURE 23

GENERAL RELATIONSHIP BETWEEN MAXIMUM AIR TEMPERATURE, PRECIPITATION AND WATER TEMPERATURE: FAIRLAND RIDGE INFILTRATION-DRY POND, JULY, 1989



defacto extended detention control, stored and slowly released this stormwater over a two-day period. In response to both the detention of relatively warm stormwater runoff and solar radiation, the July 20, 1989 inflow station posted a 4.0°F Delta-T increase (water temperature increased to 69.3°F). It is further noted that during the approximate 53 hour detention period, maximum daily air temperatures of 86 and 89°F were recorded.

- The combination of high daily maximum and minimum air temperatures, lack of shade, large rip-rap pilot channel and relatively shallow depth of stored runoff, raised July 21-22, 1989 inflow station temperatures some 4.5°F (to a high of 73.8°F). Results also showed that an additional 3.9°F Delta-T increase occurred between the lowflow orifice area and the downstream outflow station. Much of this increase is believed to have been caused by flow through warmer, open or partially shaded areas below the BMP facility. Surprisingly, the maximum outflow temperature of 77.7°F was recorded at approximately 11:40 p.m. on July 21, 1990. Inflow and outflow station temperatures both returned to normal around 5:00 a.m., July 22, 1989; some 53 hours after the start of the storm. The net Delta-T increase associated with the subject storm was 12.4°F.

Oaksprings ED Artificial Wetland

The general performance of the Oaksprings wetland under both baseflow-stormflow and inflow versus outflow conditions is graphically illustrated in Figures 24 - 27. Major results are described below and summarized in Tables 8 and 9.

1. The shallow depth (mean depth is approximately 18 inches) and small permanent pool volume, relative to the 140 acre contributory watershed, made the Oaksprings wetland and outflow station very responsive to air temperature fluctuations. The wetland's small permanent pool did, however, give it a limited ability to moderate outflow temperatures during certain small storm events.

2. Both inflow and outflow stations exhibited similar diurnal Delta-T temperature fluctuations of between 3 and $8^{o}F$. In addition, the similarity in diurnal temperature profile response during and after rainfall events suggests that the wetland's limited extended detention capability generally had little effect on outflow station temperature behavior.

3. Delta-T stormflow temperatures at the Oaksprings wetland were typically lower than Delta-T baseflow temperatures. However, approximately 65 percent of the time the difference between baseflow and stormflow Delta-T's was relatively small (i.e., $\leq 3.0^{o}F$).

4. Inflow station temperatures were negatively affected by the Upper Oaksprings wet pond. Warm water released from the upper pond site, located approximately 1700 feet upstream, frequently produced periods of extended temperature elevation at the Oaksprings inflow station.

5. The average June - August grab sampling surface water temperature (measured approximately one foot below the surface) for the Oaksprings wetland was 74.2°F.

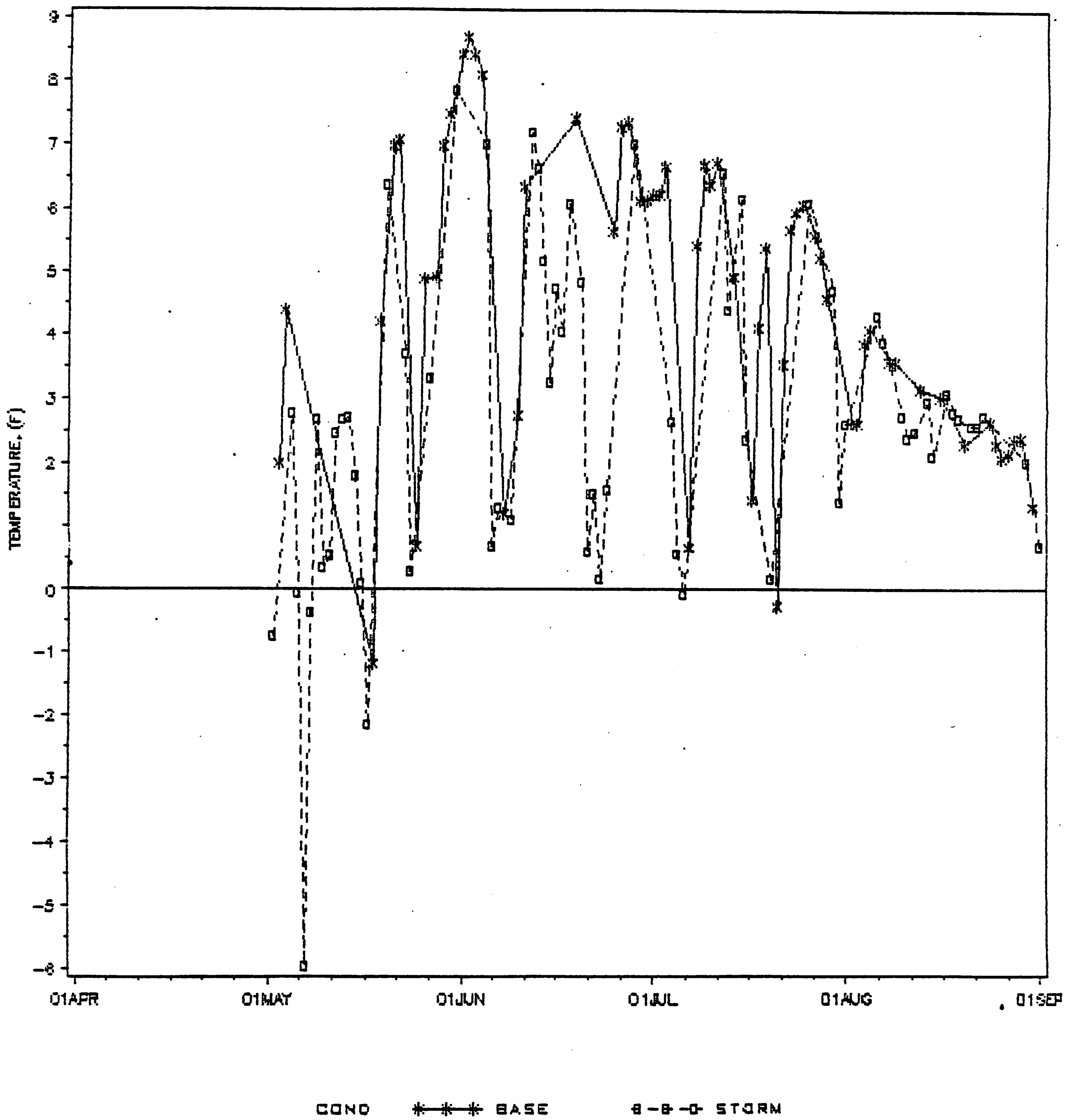
Baseflow Versus Stormflow Delta-T's

During baseflow conditions the Oaksprings wetland had both an average and maximum positive Delta-T effect of 3.9 and 8.7°F, respectively. As seen in Figure 24, maximum baseflow Delta's peaked in early June, and gradually declined thereafter. Results indicated that seasonal trends in Oaksprings BMP Delta-T performance, under both baseflow and stormflow conditions, generally paralleled seasonal air temperature fluctuations. Approximately one percent of the time, the artificial wetland had a small negative Delta-T effect.

As seen in both Figure 24 and Table 8, stormflow Delta-T's were generally smaller than baseflow Delta-T's. Average and maximum stormflow Delta-T's for the BMP were 3.2 and 7.8°F, respectively. In addition, nearly 100 percent of all stormflow Delta-T temperatures were cooler than baseflow Delta-T's. The preceding findings indicate that the artificial wetland has a limited capacity to moderate outflow station temperatures during small storm events.

FIGURE 24

ARTIFICIAL WETLAND THERMAL CHARACTERIZATION: BASEFLOW VERSUS STORMFLOW DELTA-T'S *



*Values shown are daily mean Delta-T's

Table 8 Summary: Oaksprings ED Wetland Delta-T's

Percent of Temperatures < Indicated Value	Delta-T(°F) Baseflow	Stormflow	Total
0 (minimum)	-1.2	-6.0	-6.0
1	-1.2	-6.0	-4.3
5	0.1	-0.9	-0.4
10	0.4	-0.3	0.1
25	1.3	0.7	1.1
50 (median)	3.8	2.5	2.7
75	6.2	3.9	5.4
90	7.3	6.3	7.0
95	8.2	7.0	7.4
99	8.7	7.8	8.6
100 (maximum)	8.7	7.8	8.7

Because of the wetland's small permanent pool volume, this moderating ability was highest for smaller storm events occurring during cool air temperature periods. It is further noted that the -6.0°F stormflow Delta-T recorded in the second week of May was the result of unseasonably cool, wet weather during that period.

Temperature Standard Performance

As seen in Figure 25, trends in maximum daily inflow-outflow station water temperature generally paralleled those of maximum air temperature. The same figure also shows that inflow station temperatures were more responsive to inputs of stormwater runoff than were outflow station temperatures.

Under baseflow conditions, outflow station temperatures (Figure 26) exceeded Class III and IV temperature standards 60 and 15 percent of the time, respectively. In contrast, the same standards were violated approximately 57 and 5 percent of the time, respectively under stormflow conditions.

Outflow station temperatures were higher than inflow station temperatures 95 percent of the time (Figure 26). While the stormflow Delta-T temperature difference between the two stations was generally less than 3.0°F, outflow temperatures during the warmest month of the study (July) were as much as 7.8°F higher than inflow station temperatures.

During stormflow conditions, inflow station temperatures violated Class III and IV temperature standards approximately 35 and 4 percent of the time,

FIGURE 25

GENERAL RELATIONSHIP BETWEEN MAXIMUM AIR TEMPERATURE, PRECIPITATION AND WATER TEMPERATURE: OAKSPRINGS ARTIFICIAL WETLAND, APRIL-SEPTEMBER, 1989

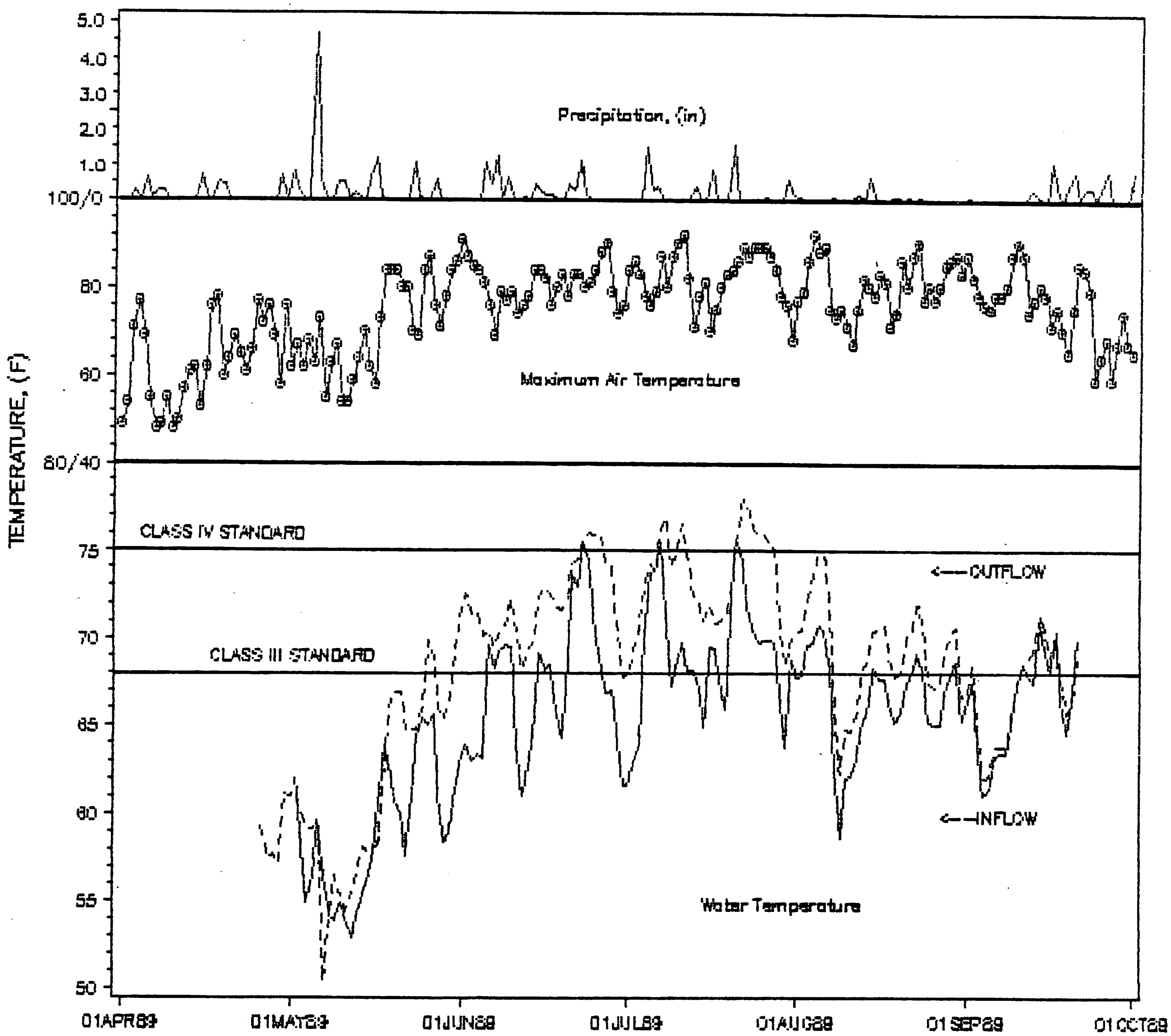
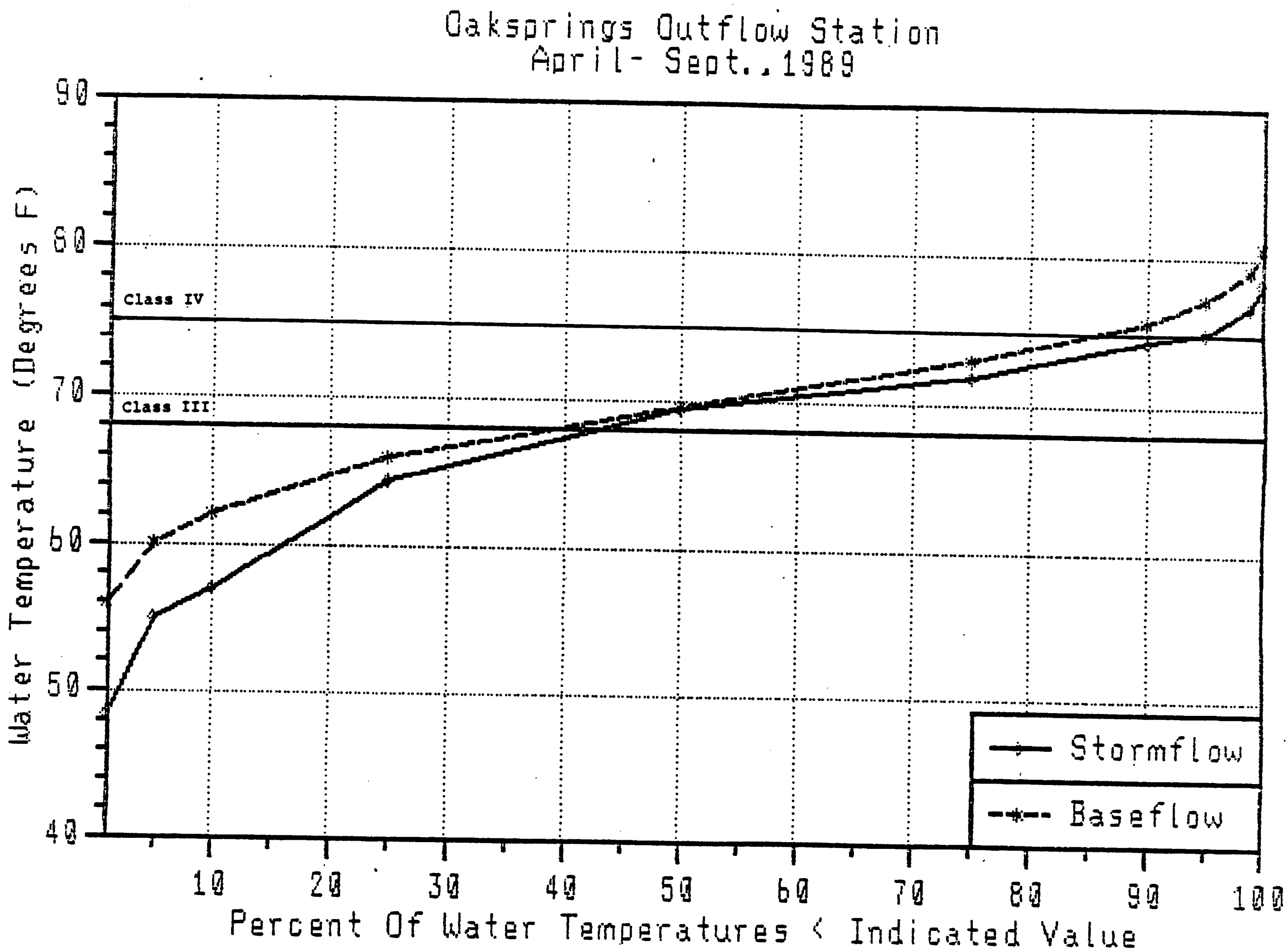


FIGURE 26

ARTIFICIAL WETLAND TEMPERATURE STANDARD PERFORMANCE: BASEFLOW VERSUS STORMFLOW CONDITIONS



respectively. In contrast, under stormflow conditions, outflow station temperatures exceeded these standards 55 and 5 percent of the time, respectively (Figure 27 and Table 9).

FIGURE 27

ARTIFICIAL WETLAND INFLOW-OUTFLOW TEMPERATURE RELATIONSHIP DURING STORMFLOW

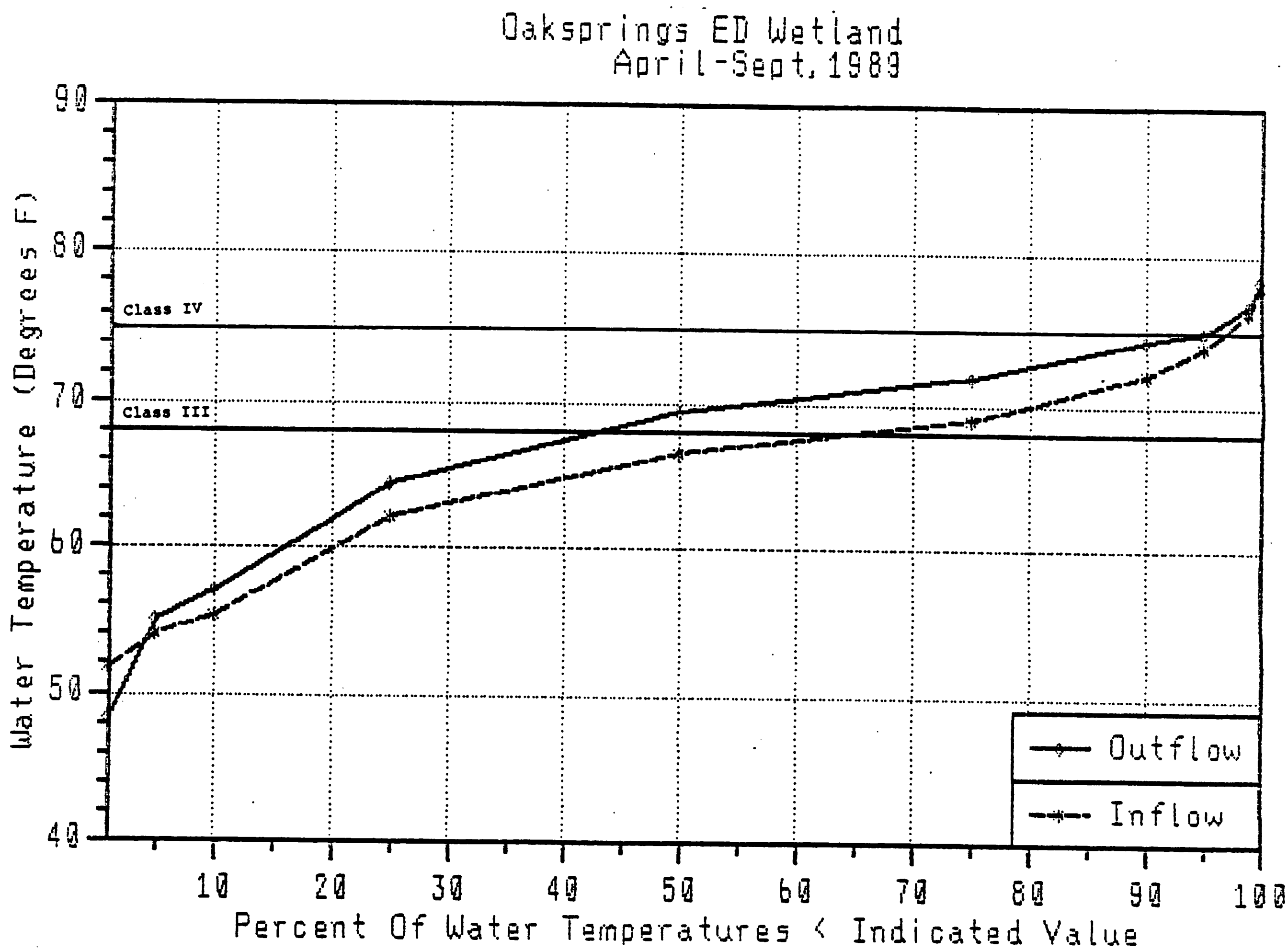


Table 9
Summary: Oaksprings ED Wetland Performance, April - Sept., 1989

Percent of Water Temperatures ≤ Indicated Value (%)	Temperature(^oF)			
	Baseflow		Stormflow	
	Inflow	Outflow	Inflow	Outflow
0 (minimum)	50.0	52.9	50.9	44.8
1	55.2	56.1	51.8	48.4
5	58.5	60.1	54.1	55.0
10	60.3	62.2	55.4	57.0
25	63.1	66.0	62.1	64.4
50 (median)	66.2	69.6	66.6	69.4
75	69.1	73.0	68.9	71.8
90	71.1	75.7	72.1	74.5
95	72.5	77.2	73.9	75.0
99	77.4	79.2	76.3	76.8
100 (maximum)	80.2	80.8	78.1	78.4

Tanglewood ED Dry Pond

As previously noted, the Tanglewood ED dry pond had both high maximum Delta-T temperatures and a high percentage of MDE Class III temperature standard violations. In addition, maximum outflow water temperatures associated with this facility were second only to those of the Countryside wet pond. The general performance of this BMP under both baseflow-stormflow and inflow versus outflow scenarios are presented in Figures 28-31. Major findings are described below and are additionally summarized in Tables 10 and 11.

1. The maximum Delta-T produced by this BMP was higher under stormflow conditions (11.2^{o}F) than under baseflow conditions (9.7^{o}F). The higher stormflow Delta-T's were the product of: a) the inflow of relatively warm stormwater runoff into the facility, b) pilot channel heat contributions, and c) additional heating of detained waters via solar radiation. In addition, the highest Delta-T's were noted during warm weather.

2. The Tanglewood outflow station had large daily Delta-T temperature swings, which were amplified by the BMP. Over the course of the monitoring period, average diurnal Delta-T temperature fluctuations at the inflow and outflow stations were, respectively, 3.6^{o}F and 5.6^{o}F. The generally wider daily Delta-T temperature range observed at the outfall station was largely the result of water being heated

by its passage through the pond's partially shaded pilot channel. It should also be noted that, of the four BMP outflow stations monitored, the Tanglewood station's diurnal temperature flux was consistently the highest.

3. During the study COG staff observed, on three separate occasions, evidence of impounded stormwater within the Tanglewood facility. However, it appeared that runoff from most small storm events either was not detained or detained for only very brief periods of time. Examination of the outflow station diurnal temperature response during and after storm events, did not reveal obvious extended detention effects.

4. Under baseflow conditions, this BMP's partially shaded pilot channel had an average positive stream Delta-T effect of 3.7°F.

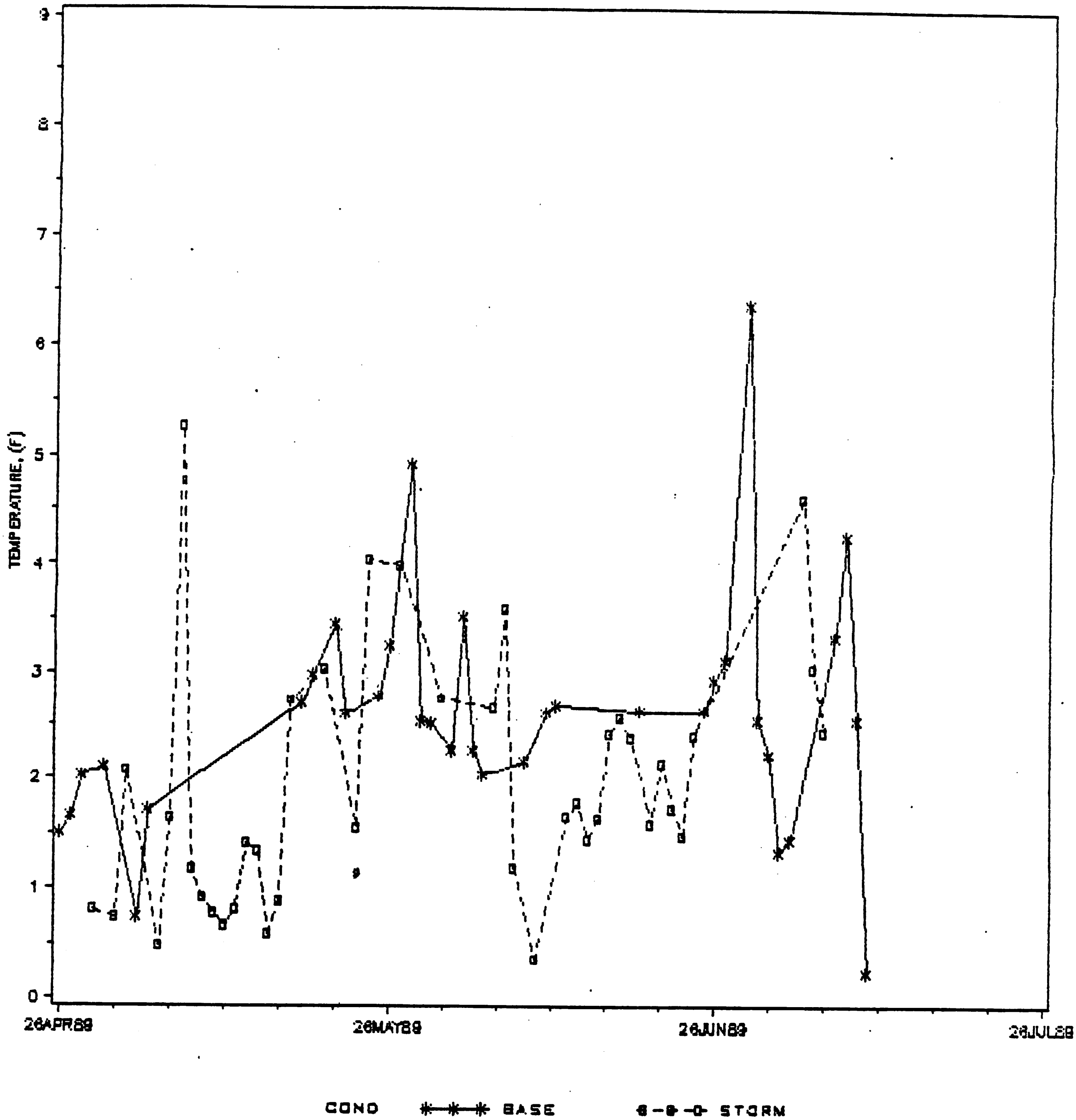
Baseflow Versus Stormflow Delta-T's

Under baseflow conditions, the Tanglewood ED dry pond had both an average and maximum positive Delta-T effect of 5.5 and 9.7°F, respectively. In general, maximum baseflow and stormflow Delta-T's coincided with warm air periods (Figure 28).

Stormflow Delta-T's were generally higher than baseflow Delta-T's approximately 25 percent of the time (Table 10). Average and maximum stormflow Delta-T's for the ED dry pond were 5.2 and 11.2°F, respectively. The 11.2 °F maximum stormflow Delta-T observed at this BMP site occurred

FIGURE 28

EXTENDED DETENTION DRY POND THERMAL CHARACTERIZATION: BASEFLOW VERSUS STORMFLOW DELTA-T'S *



*Values shown are daily mean Delta-T's

Table 10 Summary: Tanglewood ED Dry Pond Delta-T's

Percent of Temperatures < Indicated Value	Delta-T(°F) Baseflow	Stormflow	Total
0 (minimum)	2.3	1.4	1.4
1	2.3	1.4	1.4
5	2.4	1.5	1.5
10	2.6	1.9	1.9
25	3.2	2.5	3.1
50 (median)	6.1	5.3	5.9
75	7.0	7.3	7.1
90	8.0	8.6	8.6
95	8.6	9.8	9.7
99	9.7	10.9	10.9
100 (maximum)	9.7	11.2	10.9

during a warm air period which included 0.52 inches of precipitation.

Temperature Standard Performance

Outflow station temperatures (Figure 29 and Table 11) were, under stormflow conditions, slightly higher than baseflow temperatures 20 percent of the time. In addition, the frequency of MDE Class III and IV water temperature standard violations was similar under both flow scenarios. Stormflow outfall temperatures violated Class III and IV standards 48 and 15 percent of the time, respectively. The same standards, under baseflow conditions were exceeded 50 and 10 percent of the time, respectively.

Among the more revealing findings (Figure 30) was that 99 percent of all Tanglewood outflow station temperatures were, under stormflow conditions, warmer than inflow station temperatures. Examination of these two stations, under baseflow conditions, yielded similar results. As seen in Table 11, stormflow outflow station temperatures ranged from 0.0 - 5.8^{o}F higher than inflow temperatures.

A comparison of inflow versus outflow station temperatures, under stormflow conditions (Figure 30), revealed that inflow temperatures violated Class III and IV temperature standards 25 and 1 percent of the time. In contrast, Tanglewood outflow station temperatures violated the same standards 50 and 10 percent of the time, respectively. Outflow station temperature profiles did not exhibit signs of artificially produced periods of prolonged temperature elevation, reduction, or stasis. In fact, outflow temperature profiles closely paralleled those of the inflow station. The

FIGURE 29

EXTENDED DETENTION DRY POND TEMPERATURE STANDARD PERFORMANCE: BASEFLOW VERSUS STORMFLOW CONDITIONS

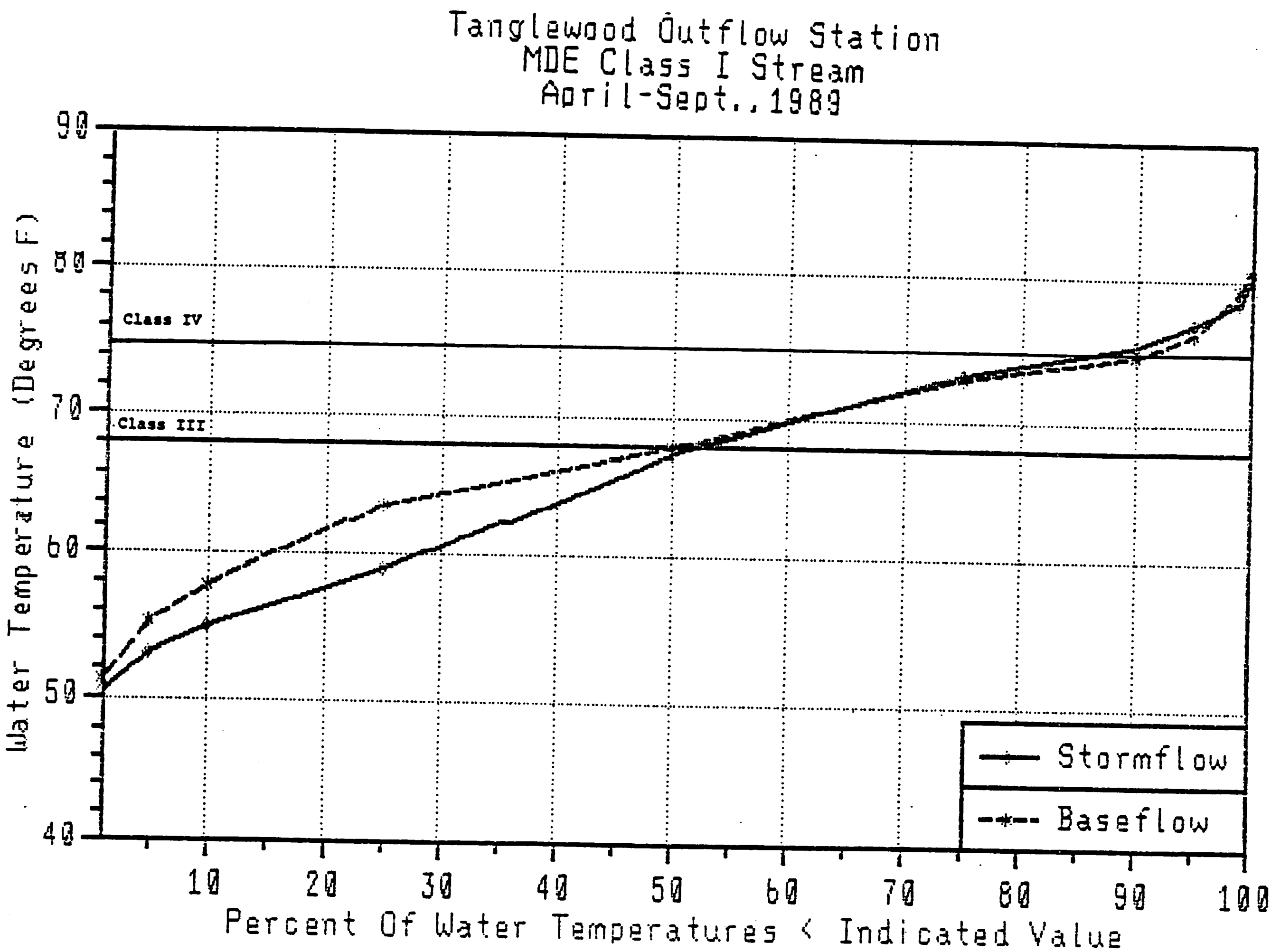
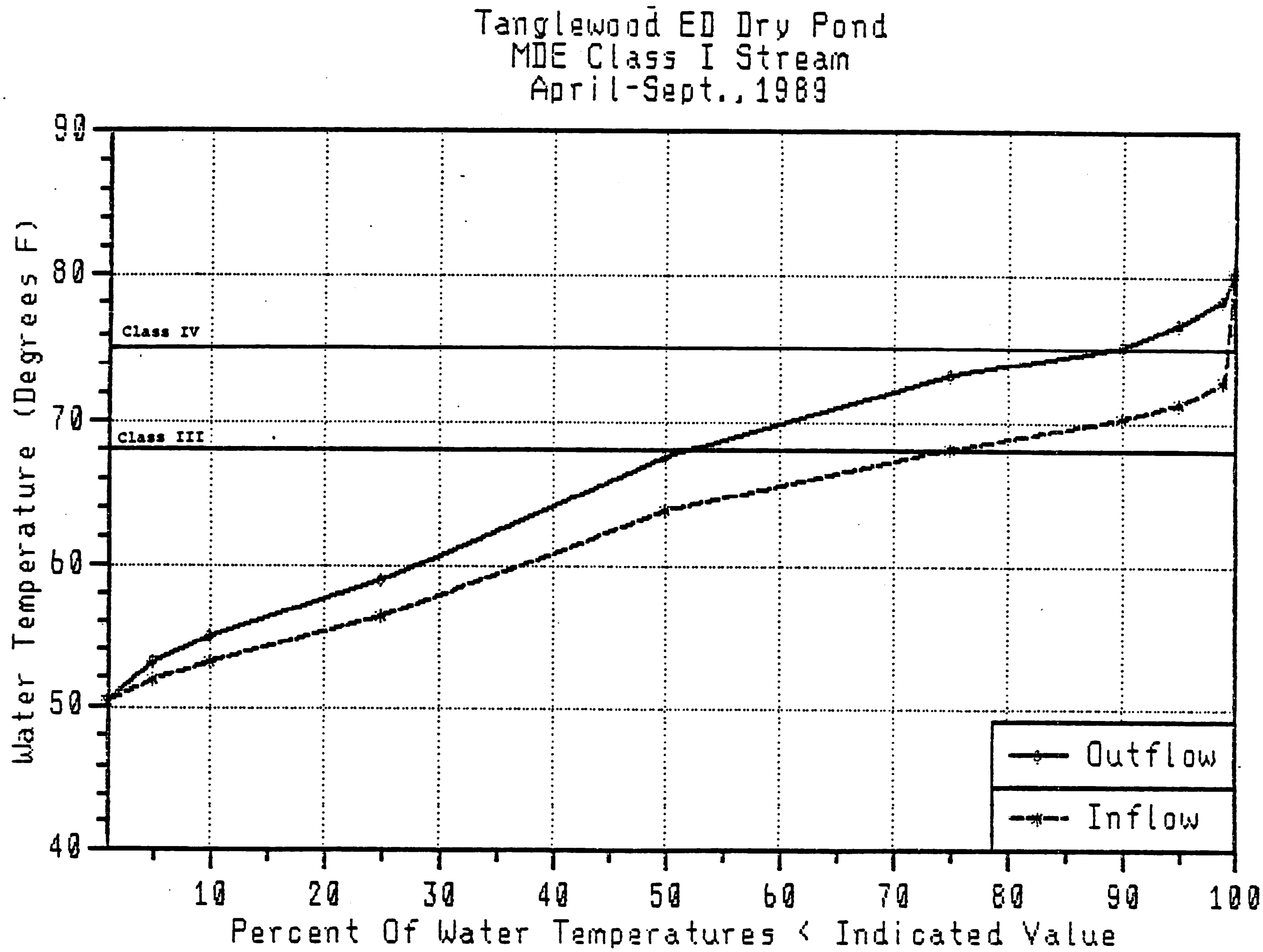


Table 11 Summary: Tanglewood ED Dry Pond Performance, April - Sept., 1989

Percent of Water Temperatures ≤ Indicated Value (%)	Temperature(°F) Baseflow Inflow	Baseflow Outflow	Stormflow Inflow	Stormflow Outflow
0 (minimum)	49.6	48.6	48.9	49.1
1	51.6	51.4	50.5	50.5
5	54.1	55.4	52.0	53.2
10	55.9	57.9	53.2	55.0
25	59.7	63.9	56.5	59.0
50 (median)	65.5	68.0	63.9	67.5
75	68.1	72.9	68.2	73.2
90	70.2	74.7	70.3	75.3
95	71.1	76.3	71.2	76.9
99	72.3	79.2	72.7	78.5
100 (maximum)	80.8	81.9	80.4	80.4

FIGURE 30

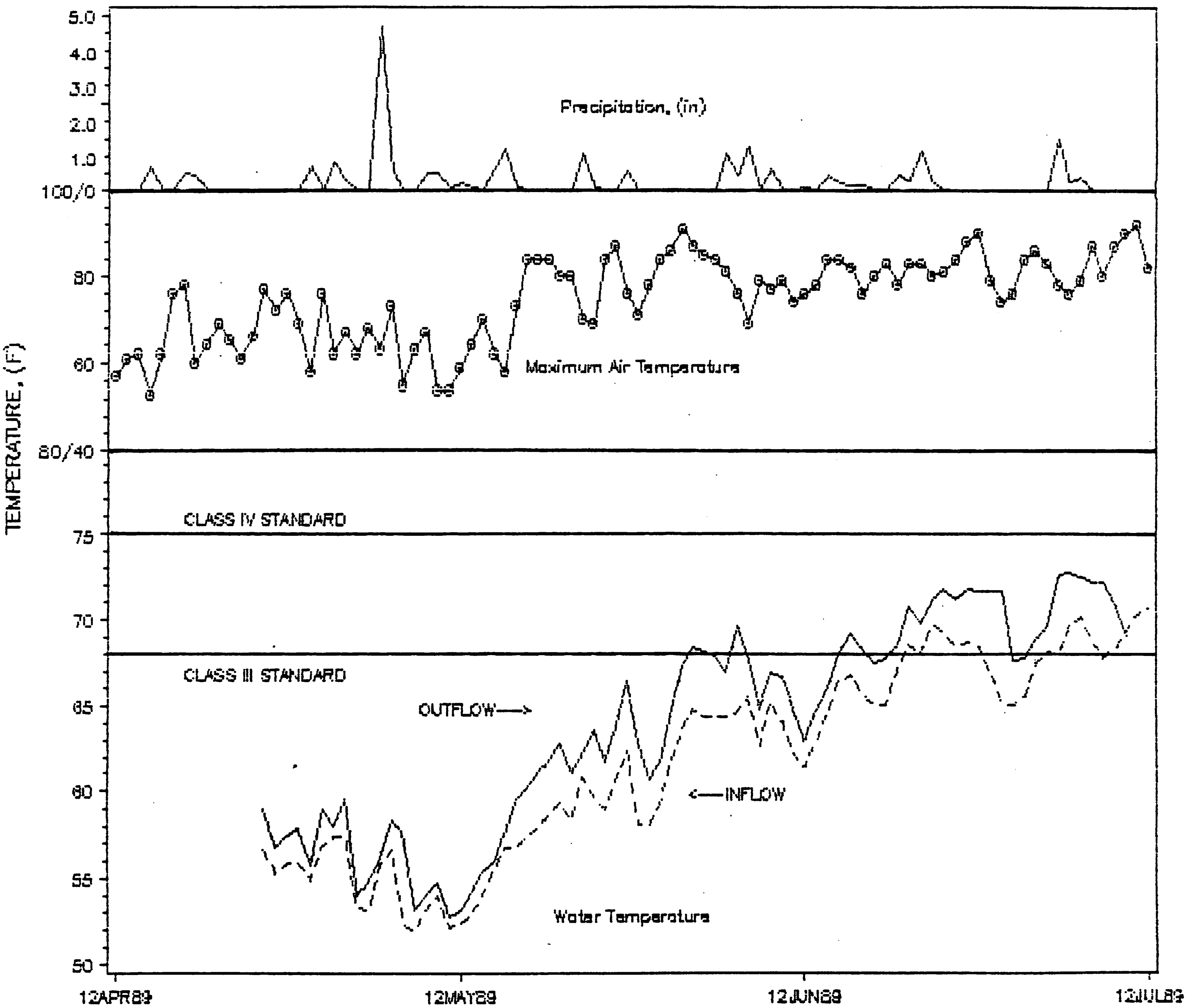
EXTENDED DETENTION DRY POND INFLOW-OUTFLOW TEMPERATURE RELATIONSHIP DURING STORMFLOW



general trends in April - July, 1989 maximum air temperature, precipitation, and Tanglewood inflow-outflow water temperatures are graphically summarized in Figure 31.

FIGURE 31

GENERAL RELATIONSHIP BETWEEN MAXIMUM AIR TEMPERATURE, WATER TEMPERATURE AND PRECIPITATION: TANGLEWOOD ED DRY POND, APRIL-JULY, 1989



Countryside Wet Pond

Shallow, surface release impoundments are often credited with raising, especially during the warmer months of the year, the water temperature of small receiving streams. During summer months it is not unusual to see the surface water temperature of lakes and ponds in the Middle-Atlantic States occasionally hovering near the 90^{o}F mark. This is particularly the case during extended hot weather periods and/or for small, shallow ponds which are heavily sheltered from the mixing-effect of the wind.

While much of the study period was cooler than normal, the Countryside outflow station proved to be the warmest of the four BMP outflow stations monitored. The general performance of this eight foot-deep, surface release wet pond under both baseflow-stormflow and inflow versus outflow conditions is graphically summarized in Figures 32-35. Significant findings from both the grab sampling and automated monitoring portions of the study are discussed below and additionally summarized in Tables 12-14.

1. The wet pond's large permanent pool served as an effective heat regulator. In general, the pond had a major warming effect on baseflow temperatures. However, during most storm events, the pond depressed the already elevated outflow station temperatures.

2. Delta-T baseflow temperatures at the Countryside wet pond were higher than stormflow Delta-T's 99 percent of the time. The average

baseflow Delta-T (9.7°F) was slightly higher than the average stormflow Delta-T (8.5°F). As previously noted, the pond's rip-rap outflow channel produced an average positive Delta-T increase of 2.0°F.

3. The average June - August, 1989 grab sampling surface water temperature in the Countryside pond was 77.8°F. This temperature was 3.6°F higher than the average temperature recorded, during the same period, in the Oaksprings wetland. The higher summer water temperatures associated with the wet pond are primarily a function of its larger permanent pool volume. The larger volume of water resulted in the Countryside pond storing and releasing heat from solar radiation more slowly; thus making it less responsive to air temperature fluctuations. Consequently, wet pond water temperatures remained generally higher throughout the summer (Table 12). In addition, the larger permanent pool volume resulted in the pond being noticeably slower to cool-down in late summer/early fall.

4. The maximum Countryside outflow station temperature, under stormflow conditions was 82.6°F. This temperature was only 1.3°F higher than the maximum outflow temperature recorded under base flow conditions (81.3°F). It should also be noted that the maximum surface water temperature observed in the pond during the grab sampling portion of the study was 86.9°F.

Table 12 Countryside Wet Pond Versus Oaksprings Wetland Surface Water Temperatures(°F), June - October, 1989

Average Surface Temperature(°F)[1/]

Month	Date	Countryside Wet Pond	Date	Oaksprings Wetland
6	15	78.4	15	70.7
	21	76.7	20	73.9
	27	86.3	27	77.4
7	6	75.3	5	75.2
			11	80.6
	11	74.0	13	75.2
	20	76.4	21	75.2
	25	73.1	26	79.3
8	2	80.6	1	69.5
	9	77.7	9	68.3
	16	76.3	17	73.0
	22	80.9	22	72.4
9	1	77.5	1	73.0
	7	72.4	7	68.9
	14	79.2	14	73.7
	20	73.0	20	67.6
	29	66.2	29	55.0
10	6	62.3	6	55.4
	13	60.8	13	51.8
	20	55.1	18	61.3

[1/]Water temperatures were measured at 2 or more locations at each BMP site.

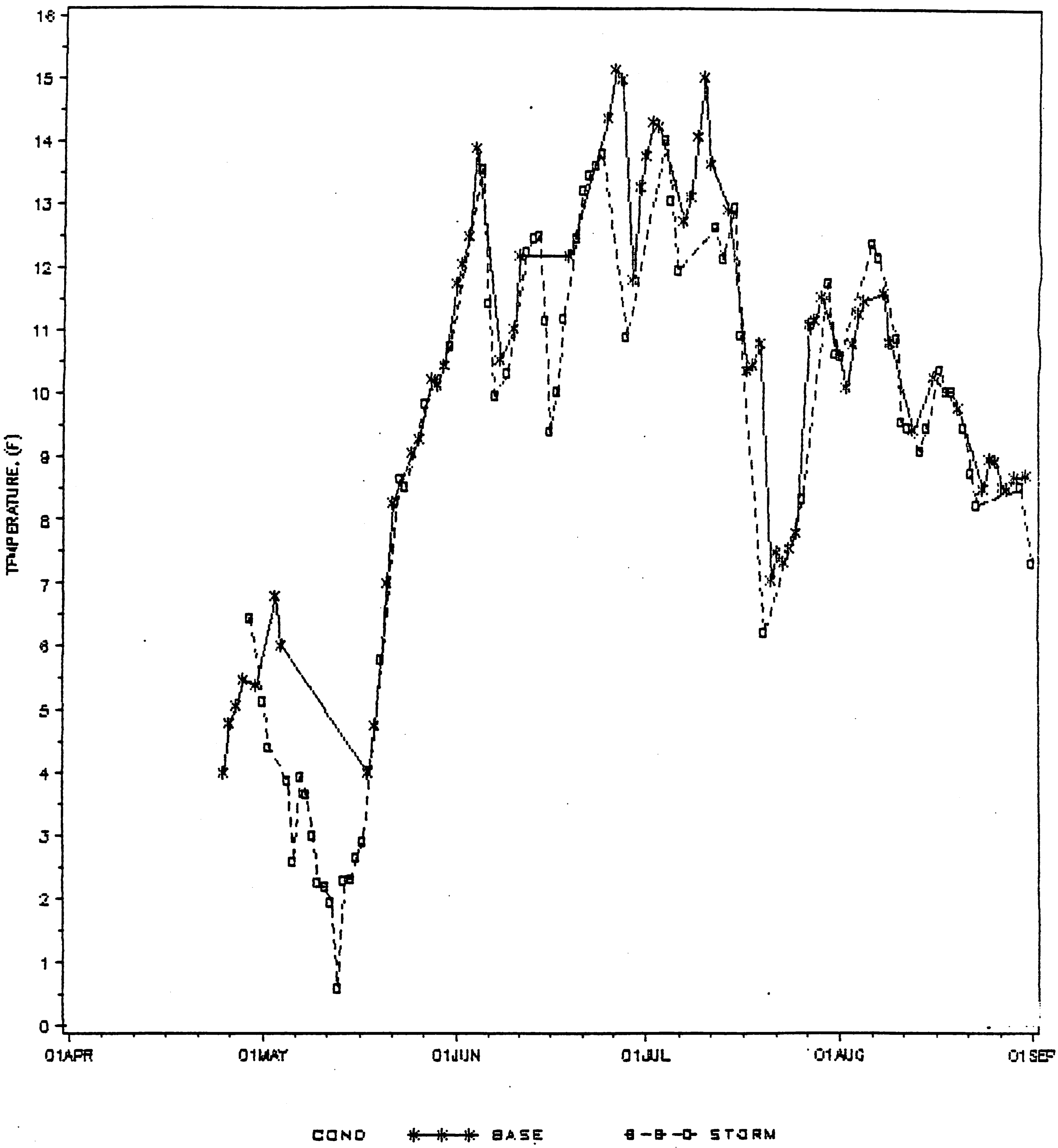
Baseflow Versus Stormflow Delta-T's

As seen in both Figure 32 and Table 13, under baseflow conditions the wet pond raised outflow station temperatures an average 9.7°F. Not surprisingly, the maximum baseflow Delta-T (15.1°F) occurred during one of the warmest periods of the study (i.e., late June - early July). By the end of the automated monitoring period (September 20, 1989), maximum baseflow Delta-T's had declined to around 8.0°F.

Both baseflow and stormflow Delta-T's were always positive during the study. However, stormflow Delta-T's were smaller than baseflow Delta-T's approximately 99 percent of the time. This indicates that most storm events lowered both pond and outflow station temperatures. Most likely, the temperature reductions were caused by cool air temperatures and/or an influx of stormwater runoff (whose temperature was lower than ambient pond temperatures). The average and maximum stormflow Delta-T's during the study were 8.5 and 14.0°F, respectively.

FIGURE 32

WET POND THERMAL CHARACTERIZATION: BASEFLOW VERSUS STORMFLOW DELTA-T'S *



*Values shown are daily mean Delta-T's

Table 13 Summary: Countryside Wet Pond Delta-T's

Percent of Temperatures < Indicated Value	Delta-T(°F) Baseflow	Stormflow	Total
0 (minimum)	4.0	0.6	0.6
1	4.0	0.6	1.3
5	4.8	2.2	2.6
10	6.0	2.6	4.0
25	7.3	5.7	6.7
50 (median)	9.6	9.5	9.5
75	11.8	11.7	11.8
90	13.9	13.0	13.4
95	14.4	13.6	14.1
99	15.1	14.0	15.1
100 (maximum)	15.1	14.0	15.1

Temperature Standard Performance

Under stormflow conditions (Figure 33), Countryside outflow station temperatures were typically 0.5 - 5.9°F lower than under baseflow condition. In addition, both MDE Class III and IV temperature standards were more frequently exceeded under baseflow conditions. Outflow station temperatures violated Class III and IV temperature standards (under baseflow and stormflow conditions) 77 and 35 percent, and 64 and 25 percent of the time, respectively.

Outflow station temperatures (under stormflow conditions) were higher than inflow station temperatures 100 percent of the time. As seen in Figure 34, the much cooler Countryside inflow station (under stormflow conditions) violated Class III and IV temperature standards 10 and 1 percent of the time, respectively. The median outflow station temperature under both baseflow and stormflow conditions (Table 14) were approximately 11.0°F higher than the median inflow station temperatures.

Examination of the water temperature data also revealed that the maximum stormflow outflow station temperature occurred on a date (August 6, 1989) in which a maximum of only 0.05 inches of rain fell in the vicinity of the Countryside pond. Additional review of air temperature data indicated that this maximum outflow water temperature coincided with a warm to hot air temperature period.

During this warm air period, maximum air temperatures ranged between 86

FIGURE 33

WET POND TEMPERATURE STANDARD PERFORMANCE: BASEFLOW VERSUS STORMFLOW CONDITIONS

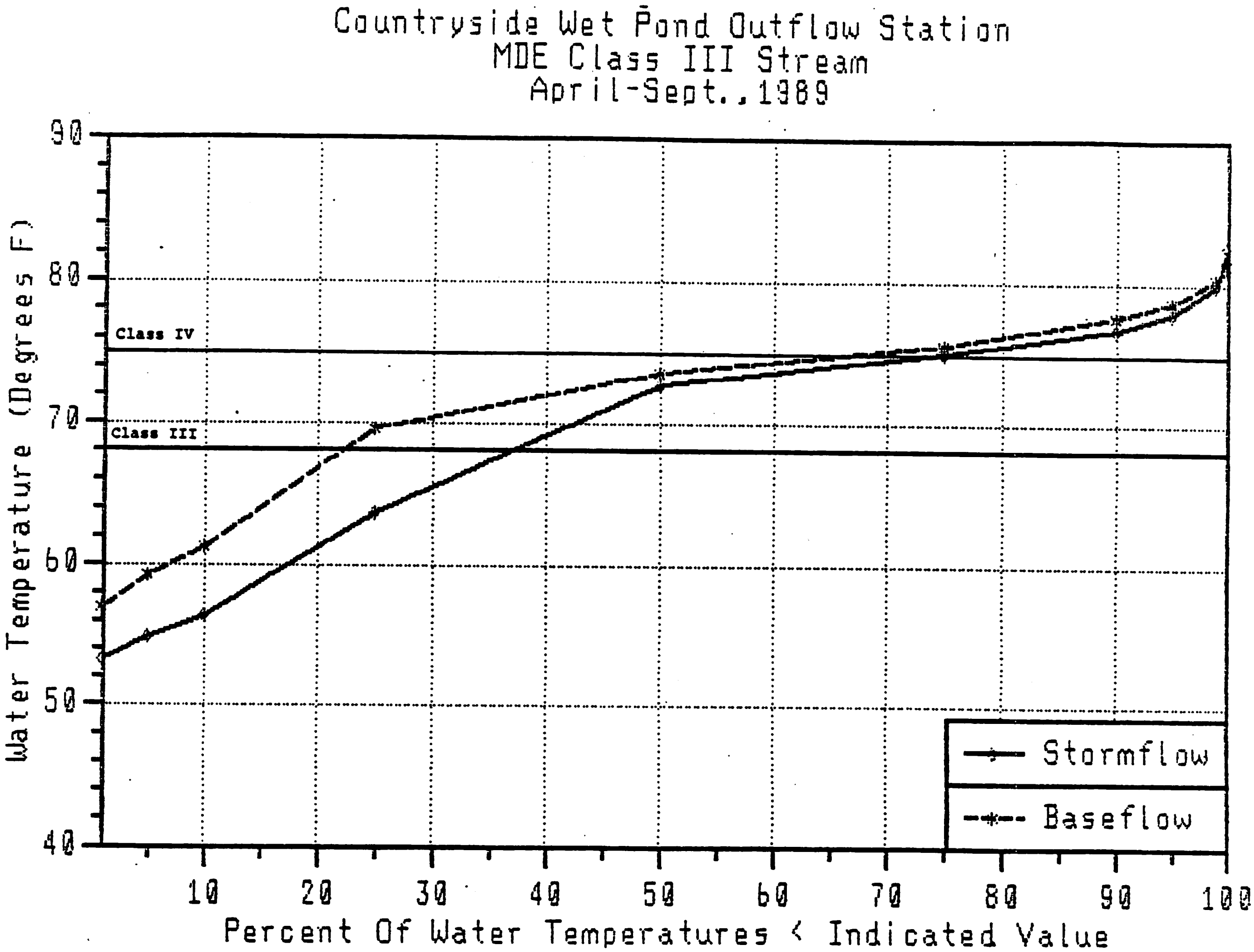


FIGURE 34

WET POND INFLOW-OUTFLOW TEMPERATURE RELATIONSHIP DURING STORMFLOW

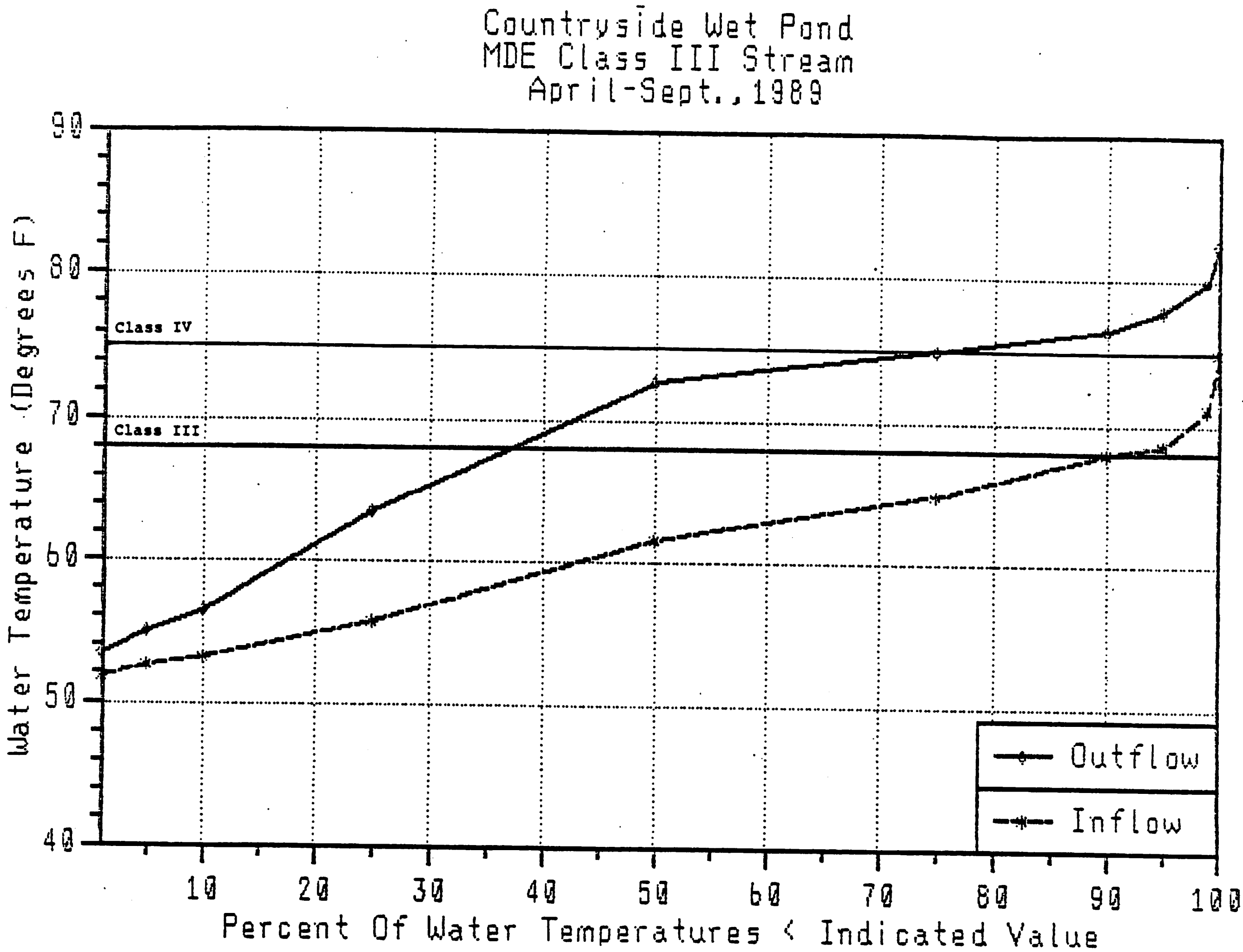


Table 14 Summary: Countryside Wet Pond Performance, April - Sept., 1989

Percent of Water Temperatures ≤ Indicated Value (%)	Temperature (°F) Baseflow Inflow	Baseflow Outflow	Stormflow Inflow	Stormflow Outflow
0 (minimum)	47.7	55.9	49.6	50.5
1	50.0	57.0	52.0	53.4
5	54.1	59.2	52.7	55.0
10	55.0	61.3	53.2	56.3
25	58.6	69.6	55.8	63.7
50 (median)	63.0	73.8	61.7	72.7
75	66.7	75.9	64.9	75.0
90	68.4	77.7	68.0	76.8
95	69.1	78.6	68.5	77.9
99	70.2	80.4	71.1	79.9
100 (maximum)	70.7	81.3	77.9	82.6

and 92^{o}F for four straight days. Therefore, in all likelihood the 82.6^{o}F outflow station temperatures was the result of high air temperatures raising pond water temperatures, rather than a discharge of warm stormwater runoff-pond spillover.

2. Example of Summer Thunderstorm Effect

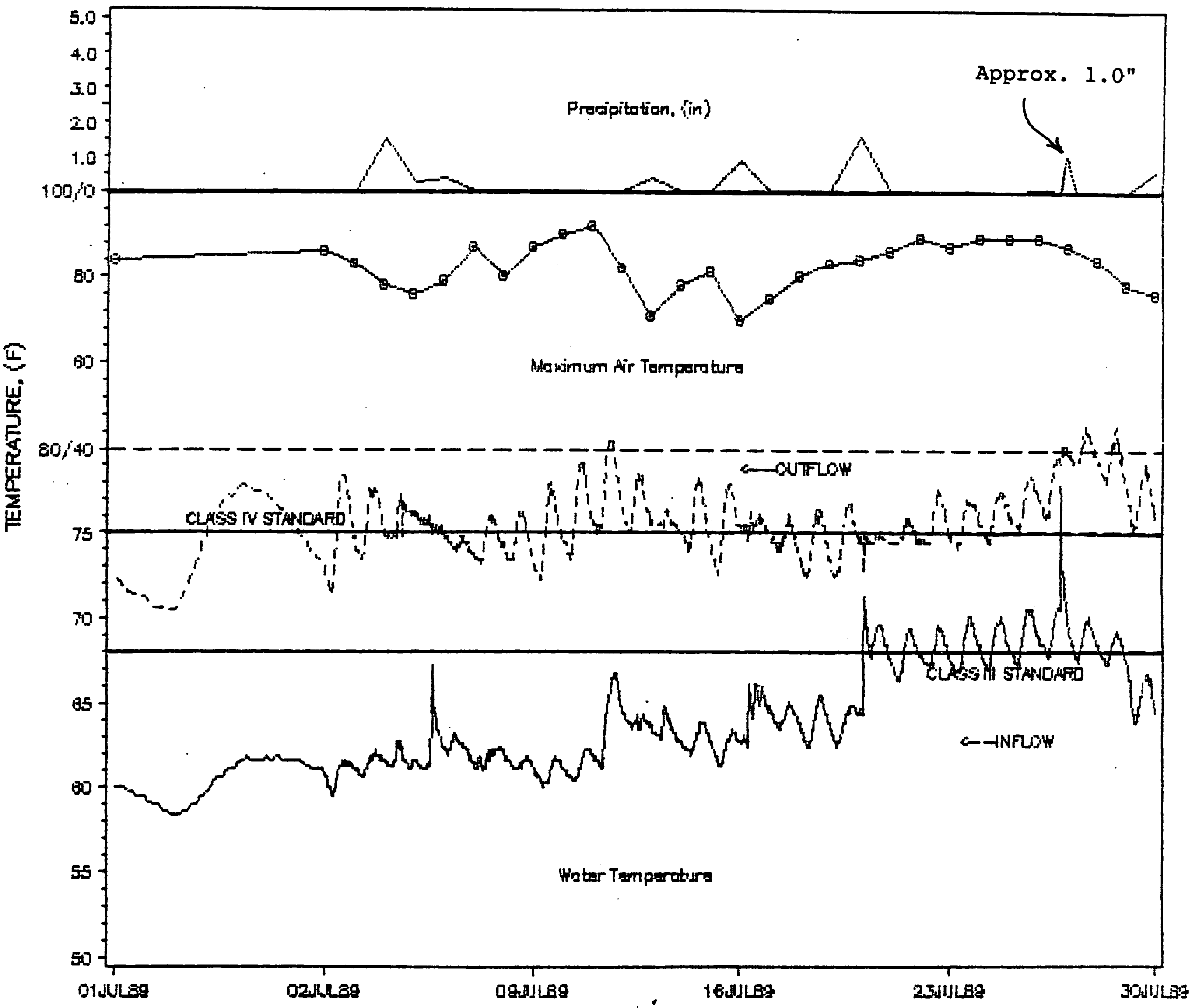
Thermograph thermometer results indicated that the Countryside inflow station exceeded the 75^{o}F Class IV temperature standard on only one occasion. The violation, which occurred on July 26, 1989 (Figure 35), coincided with an intense afternoon thunderstorm. During this storm event, water temperatures at the inflow station rose 9.0^{o}F within two hours, to a high of 77.9^{o}F. The principal factors which are thought to have contributed to this high stream temperature are briefly outlined below:

- The high stream temperature occurred on a date in which the air temperature in the study area was a hot, 91^{o}F. In addition, five consecutive warm days and nights preceded the storm date. Average daily high and low air temperatures during this five-day period were 88.0 and 72.2^{o}F, respectively. As seen in Figure 35, stream temperatures during the same period responded to the warm air temperatures by also becoming warmer. It is also quite probable that ground temperatures responded in an analogous fashion.

- While only a trace amount of rainfall was reported at the Glenmont, MD weather station, intense local thunderstorms were reported in the

FIGURE 35

GENERAL RELATIONSHIP BETWEEN MAXIMUM AIR TEMPERATURE, PRECIPITATION AND WATER TEMPERATURE: COUNTRYSIDE WET POND, JULY, 1989



vicinity of the Countryside pond. Reports from Messrs. Friedman and Swanson, two independent NOAA weather reporters whose stations are both located approximately 1.5 miles from the pond site, indicated that between 0.70 and 1.28 inches of precipitation was associated with this 5:00 - 7:00 p.m. storm. Thus, significant volumes of stormwater runoff were quickly generated from the 12 percent impervious catchment area.

- In a recent study of a small, urban Maryland stream system, Galli (1988), reported that the temperature of stormwater runoff during hot weather periods can exceed 84°F. The study also noted that even after 55 minutes of steady rain from a 1.0 inch storm the temperature of stormwater runoff did not decrease substantially. As such, large quantities of warm stormwater runoff would have been expected to have been generated from the residential and commercial portions of the Countryside subwatershed.

- Baseflow at the Countryside inflow station was, on July 25th, only 0.16 cfs. This flow, which was approximately one-third below the station's average discharge of 0.25 cfs, would have comprised a minor portion of the total stream flow during the July 26th storm event.

Although a large number of the storm events which took place during the study had an overall cooling effect on stream temperatures, the preceding result demonstrates that moderately-sized rainfall events which occur during hot weather periods are capable of markedly increasing the temperature of small, lightly developed urban streams.

3. Thermal Loading As A Function of Flow Ratio

It has already been shown that the introduction of large quantities of stormwater runoff into small, urban headwater streams, can under certain meteorological conditions, sharply alter normal diurnal stream temperature patterns. For instance, the mixing of relatively large quantities of stormwater runoff with baseflow on July 26 and 27, 1989, quickly raised stream temperatures 9.0^{o}F and 5.8^{o}F, respectively, at the Countryside inflow and Lower White Oak stations. According to Pluhowski (1970), the impact of stormwater runoff on receiving stream temperature patterns increases as the ratio of runoff to total streamflow increases.

To test the validity of this theory, COG staff examined the effect of thermal discharges from the Oaksprings artificial wetland on the Delta-T temperature response of the Gum Springs tributary. Water temperature and stream discharge grab sampling data collected from the Lower Oaksprings, Upper Gum Springs, and Gum Springs stations, were used to perform a simple linear regression of thermal loading versus flow ratio. In this test, the Upper Gum Springs station served as the reference station against which Delta-T temperature responses at the more downstream Gum Springs station were calculated. Data from a total of 10 separate sampling dates, collected between June - October, 1989 were used in the regression calculation. It is further noted that seven of these sampling dates were under the influence of stormwater discharge from the Oaksprings wetland.

Results from the analysis revealed that a distinct linear relationship exists between the Delta-T temperature response of the Gum Springs tributary and the flow ratio of the two streams. An approximation of the thermal response of the Gum Springs tributary to different Oaksprings tributary outflow conditions can be made from the following equation:

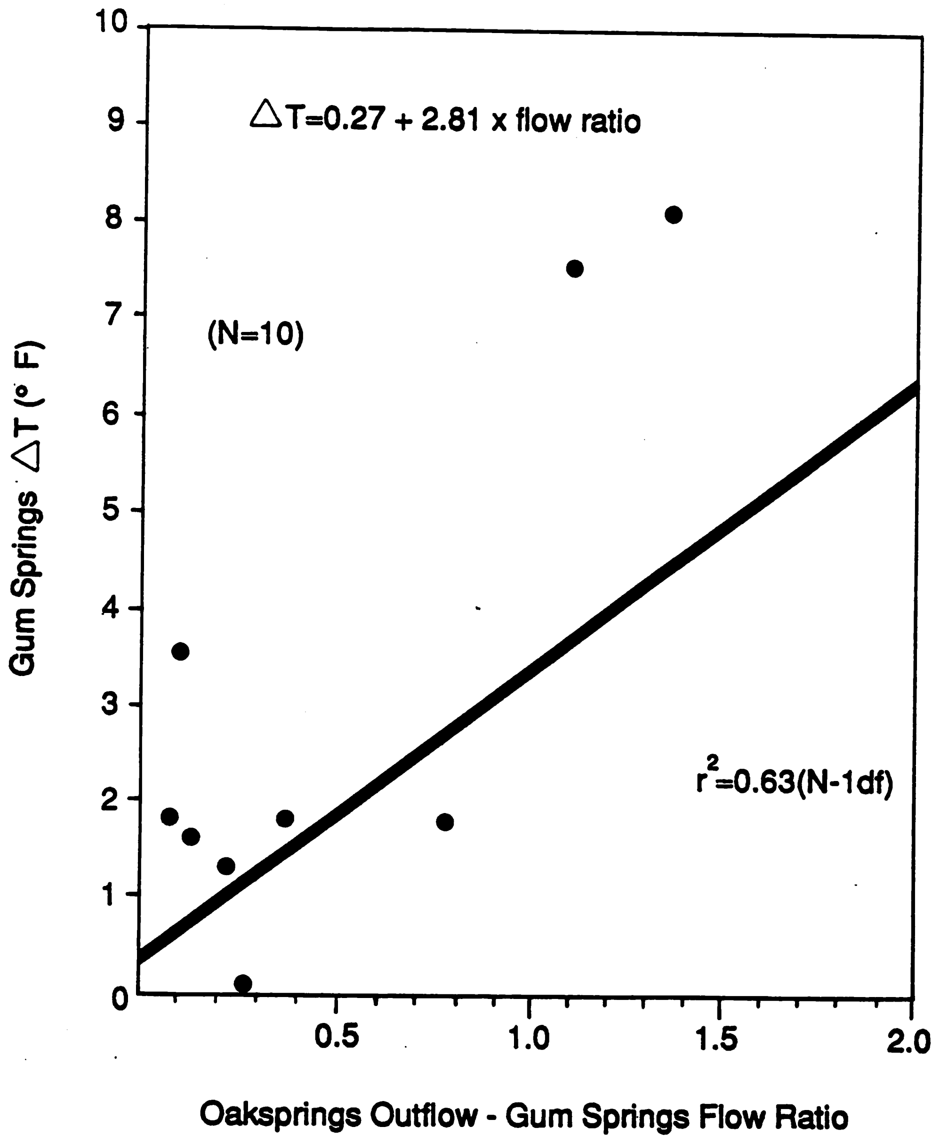
Gum Springs Delta-T(^{o}F) = 0.27 + 2.81(Flow Ratio) (between Gum Springs & Oaksprings tributary)
(thermal response)

The least squares linear regression yielded a correlation coefficient (r2), adjusted for degrees of freedom, of 0.63; indicating a moderately strong general relationship between water temperature response and flow ratio. Although the predicted Delta-T temperature increases were somewhat lower than observed Gum Springs values, both supported the previously stated findings of Pluhowski, (1970).

As seen in Figure 36, when the Oaksprings-Gum Springs tributary flow ratio is 1:1, a 3.0^{o}F Gum Springs Delta-T increase would be expected. At a 2:1 flow ratio, the expected Delta-T increase is doubled to 6.0^{o}F. The preceding results demonstrate that the potential thermal impact of stormwater runoff on receiving streams increases as the runoff (Q_{in}) to receiving stream flow (Q_r) ratio increases.

FIGURE 36

THERMAL LOADING AS A FUNCTION OF RUNOFF TO RECEIVING STREAM FLOW RATIO



4. Stormwater Management Design Elements Which Add To Thermal Load

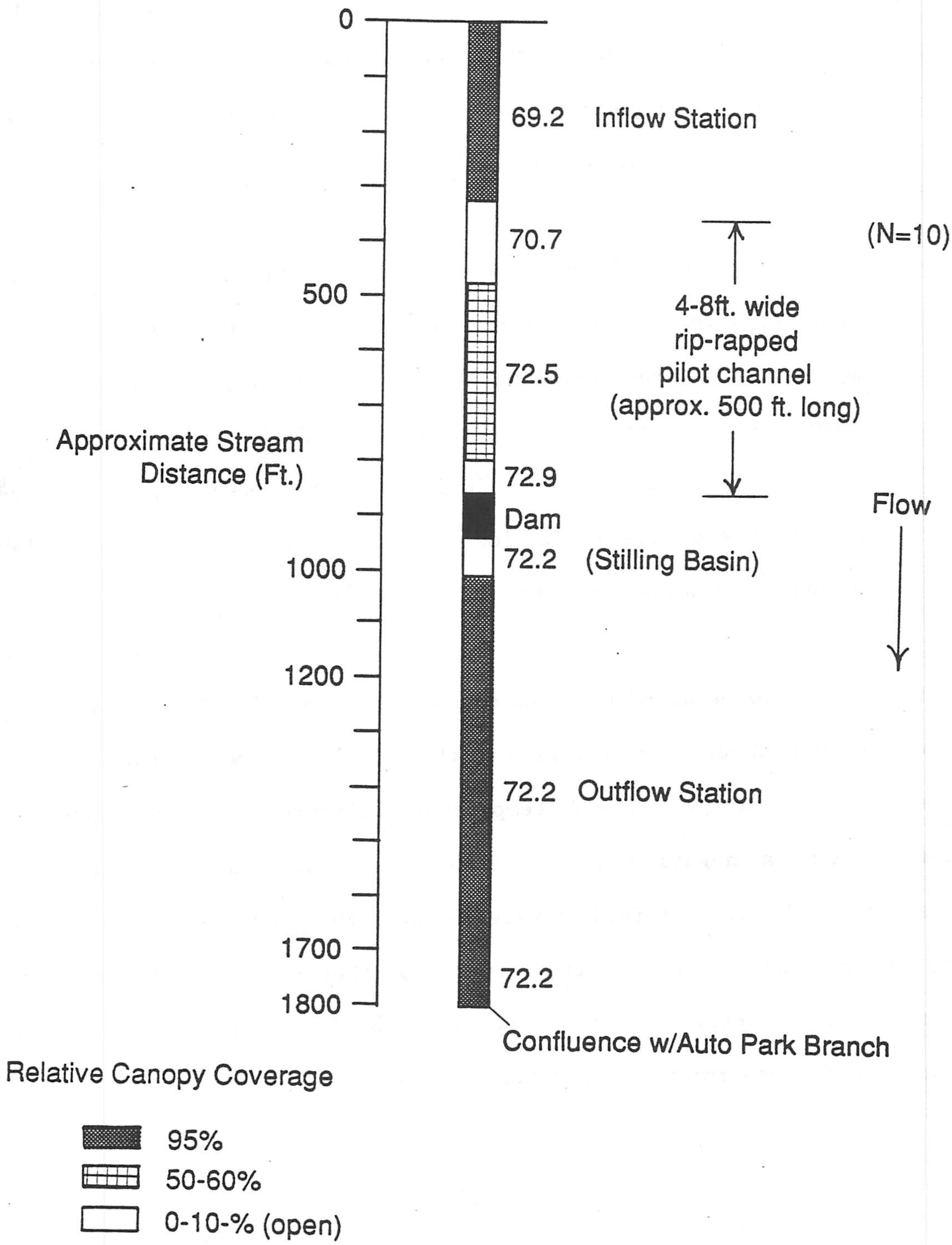
During the grab sampling portion of the study it became very clear that basic BMP facility design elements, such an inflow - outflow channels can add measurably to downstream thermal loading. This is particularly the case when these conveyance channels are unshaded, heavily rip-rapped, or both. Major findings from two BMP test sites, Tanglewood ED dry pond and Countryside wet pond, are described in detail in the following sections.

Tanglewood Pilot Channel

One of the noteworthy features of the Tanglewood facility is its rather long, flat pilot channel. Both base and storm flows are carried by the 4 - 8 foot wide x 500 foot long rip-rapped channel. As depicted in Figure 37, the pilot channel is partially shaded along its length by a narrow strip of 8 - 12 foot high black willow (Salix nigra) trees. Approximately 175 feet of the channel is open and only marginally shaded by herbaceous vegetation. The lack of adequate shading along the channel results in a net mean baseflow Delta-T increase of almost 4.0^{o}F at the riser. Although a slight decrease in mean baseflow temperature occurred as water flowed through the 60 foot long, 48 inch diameter RCP barrel, lower Tanglewood tributary baseflow temperatures remained elevated (even after flowing through 800 feet of forested buffer).

Figure 37

Effect of Partially Shaded Pilot Channel on Tanglewood ED Dry Pond Mean Baseflow Temperature(° F) (June-August, 1989)



Countryside Barrel - Outflow Channel Temperature Relationship

The Countryside wet pond features a 60 foot long, 72 inch diameter RCP barrel which discharges into a 75 foot long by 30 foot wide rip-rap outflow channel. This unshaded, trapezoidal shaped channel has a bottom width of approximately 12 feet. Under normal conditions, baseflow completely fills the bottom of the rock strewn channel. The average depth of flow, under baseflow conditions, is approximately 1 - 3 inches.

Both the length and unshaded nature of the outflow channel raised COG staff's suspicions that it may have been additionally increasing downstream water temperatures. Grab sampling results (Table 15) revealed that mean baseflow temperatures were raised as much as 8.5^{O}F after flowing through the outflow channel. On average, a 2.0^{O}F Delta-T increase was produced by the combination of lack of shade, shallow depth of flow, and presence of large, heat absorbing rip-rap associated with this channel.

It should also be noted that, on one occasion, a Delta-T decrease of 9.9^{O}F was observed between pond waters (at the dam) and flow at the end of the barrel. The average Delta-T temperature difference between these two locations was a negative 3.3^{O}F. Based on limited sampling results, it appears that the 10 foot fall of water between the pond's eight inch diameter pipe outlet and invert of the riser, together with cool barrel and air temperatures in these structures, were responsible (through convection and conduction forces) for the temperature decrease.

Table 15 Countryside Wet Pond Outflow Channel Temperature Study

June - August 1989

GRAB SAMPLE LOCATION	SAMPLE SIZE	WATER TEMPERATURE (degrees F) MAX	MIN	MEAN	MAX OBSERVED TEMP INCREASE
End of 72" RCP barrel	10	76.6	71.2	74.1	-
End of 75' rip-rap outfall channel	9	79.7	72.5	76.1	+ 8.5

Summary

Results from the study indicated that all four of the BMP facilities had positive average total Delta-T's and each violated MDE Class III and IV temperature standards some of the time. Wet permanent pools, long periods of extended detention, and poorly shaded pilot and outflow channels contributed greatly to the problem. The thermal performance of each BMP is summarized in Table 16. Specific findings are presented below.

1. Infiltration-Dry pond

- Of the four BMP's, the infiltration-dry pond produced the smallest Delta-T increases (Table 16). The infiltration trench portion of the BMP, designed for 0.25 inches of street runoff, worked well during small storms. However, large storm events (i.e., $\geq$ 1.0 inches precipitation) and/or 2 - 3 consecutive days of moderate rainfall generally overtaxed the capacity of the infiltration trench system. This often resulted in the ponding of several feet of runoff in the dry pond area. The facility's defacto extended detention control combined with high incoming solar radiation on the unshaded rip-rap pilot channel, storage pool, and outfall area, produced a 4.0^{o}F Delta-T increase.

- From a water temperature standards perspective, this BMP had the lowest frequency of Class III (68.0^{o}F) and IV (75.0^{o}F) violations (Table 16). Standards violations were more frequently associated with stormflow conditions. The BMP's single Class IV violation was

Table 16 Summary: BMP Temperature Performance1/

Parameter	Infiltration-Dry Pond	Extended Detention Wetland	Extended Detention Dry Pond	Wet Pond
	BMP Type			
Average Baseflow Delta-T (°F)	2.6	3.9	5.5	9.7
Maximum Baseflow Delta-T (°F)	7.6	8.7	9.7	15.1
Average Stormflow Delta-T (°F)	2.3	2.4	5.2	8.5
Maximum Stormflow Delta-T (°F)	5.0	7.8	11.2	14.0
Average Total Delta-T (°F)	2.5	3.2	5.3	1.1
Maximum Total Delta-T (°F)	7.6	8.7	10.9	9.1
Percent Baseflow - Class III (68°F)	8	60	50	77
Violation of MDE - Class IV (75°F)	1*	15	10	35
Temperature Stds. - Class I (90°F)	0	0	0	0
Percent Stormflow - Class III (68°F)	18	57	48	64
Violation of MDE - Class IV (75°F)	0	5	15	25
Temperature Stds. - Class I (90°F)	0	0	0	0
Maximum observed outflow water Temp (F)	77.7	80.8	81.9	82.6

1/ - Total Delta-T values shown represent combined baseflow and stormflow temperatures (i.e., all flow conditions).

* - Class IV violation result of defacto extended-detention control.

a product of a large storm and 53 hours of extended detention.

- The thermal performance of the infiltration - dry pond could have been improved had its infiltration design treatment capacity been sized to handle more than 0.25 inches of runoff from roadway areas. For thermally sensitive watersheds, such as those which support naturally reproducing trout populations, infiltration systems should be intentionally oversized. Results also showed that the infiltration-dry pond's lengthy extended detention control was a major thermal loading factor. For this reason, the use of extended detention BMP's in thermally sensitive areas should be carefully evaluated. It is further recommended that a maximum 6-12 hour detention period limit be established for these areas and that shading of the storage pool area be required.

2. Extended Detention Artificial Wetland

- The average and maximum BMP Delta-T's associated with the wetland were 3.2 and 8.7^{o}F, respectively. As seen in Table 16, Delta-T stormflow temperatures at the wetland were typically lower than baseflow Delta-T temperatures. However, approximately two-thirds of the time the difference between baseflow and stormflow Delta-T's was relatively small (i.e., $\leq$ 3.0^{o}F).

- The shallow depth (mean depth is approximately 18 inches) and small permanent pool volume, relative to the 140 acre contributory watershed, made the wetland and its outflow station very responsive to air temperature fluctuations. The wetland's small permanent pool did, however, give it a limited ability to moderate outflow temperatures during certain small storm events.

In addition, because the wetland's extended detention capacity was extremely limited, it had little influence on outflow station temperature behavior.

- Under baseflow conditions, wetland outflow station temperatures exceeded Class III and IV temperature standards 60 to 15 percent of the time, respectively. In contrast, the same standards were violated approximately 57 and 5 percent of the time, respectively under stormflow conditions. Outflow stations were higher than inflow station temperatures 95 percent of the time.

3. Extended detention Dry Pond

- Surprisingly, the ED dry pond had the second highest recorded Delta-T's (Table 16). The maximum Delta-T produced by this BMP was slightly higher under stormflow conditions (11.2^{o}F) than under baseflow conditions (9.7^{o}F). Higher stormflow Delta-T's were the product of: a) the influx of relatively warm stormwater runoff into the facility, b) the partially shaded pilot channel's heat contribution, and c) additional heating of detained waters via solar radiation. In addition, the highest stormflow Delta-T's were noted during hot weather. This BMP's 500 foot long pilot channel produced an average positive stream Delta-T of 3.7°F.

- Under stormflow conditions, the ED dry pond violated Class III and IV temperature standards 48 and 15 percent of the time, respectively.

4. Wet Pond

- The wet pond's large permanent pool served as an effective heat regulator. In general, the pond had a major warming effect on baseflow temperature. However, during most storm events, both pond and outflow station temperatures were depressed. The relatively large permanent pool volume resulted in the pond slowly storing and releasing solar radiation/heat; thus making it slow to respond to air temperature fluctuations. Average summer pond surface water temperatures remained generally over 77°F. Pond waters were noticeably slow to cool-down in late summer/early fall.

- Delta-T baseflow temperatures at the wet pond were higher than stormflow Delta-T's 99 percent of the time. The average baseflow Delta-T (9.7°F) was slightly higher than the average stormflow Delta-T (8.5°F). The pond's rip-rap outflow channel produced an average positive Delta-increase of 2.0°F.

- From a water temperature standards perspective, this BMP had the highest frequency of Class III and IV temperature standards violations. As seem in Table 16, violations were more frequent under baseflow conditions.

5. Storm-Size/Watershed Imperviousness Factor

- Results indicated that with increasing levels of watershed imperviousness, the storm-size needed to produce large stream temperature fluctuations decreased. At a 12 percent watershed imperviousness level over 0.7 inches of rainfall was generally required. In contrast, at a 60 percent imperviouness level less than 0.2 inches of precipitation was needed to produce a comparable temperature change. It should be noted that stormwater inflow generally produced positive stream Delta-T's.

6. Thermal Loading As A Function of Flow Ratio

Results revealed that a linear relationship exists between the positive Delta-T response of the receiving stream and the runoff (Q_{in}) to streamflow (Q_r) ratio. The potential thermal impact of stormwater runoff on receiving streams increased as the ratio of runoff (Q_{in}) to receiving stream flow (Q_r) increased. Not surprisingly, small headwater streams with low baseflow rates are at greatest risk from large inputs of stormwater runoff.

C. Dissolved Oxygen Monitoring Results

The two-fold purpose of the dissolved oxygen (DO) monitoring portion of the study was to: 1.) determine whether or not the four BMP's and/or their associated discharges were violating MDE water quality standards, and 2.) quantify any "downstream effect" if they in fact existed. As part of its water quality grab sampling effort, COG staff took (at its 55 station network) nearly 800 DO readings. Dissolved oxygen measurements were taken at discrete longitudinal intervals both upstream and downstream of BMP sites, as well as, within each BMP facility. While the majority of these readings were taken during baseflow conditions, approximately 100 were made under the influence of stormwater discharge. Dissolved oxygen monitoring results are summarized in Table 17. A brief general description of the major findings are presented below.

General Findings

Dissolved oxygen concentrations at the 55 sampling stations were normally well-above the state standard for their respective water use class. In general, cold well-aerated streams, such as the Lakemont tributary, had the highest DO concentrations. During the study, the DO levels in these stream areas were frequently at or above 10.0 mg/L. Even relatively warm, heavily urbanized stream reaches such as the Lower White Oak tributary remained well-oxygenated. Much of this is attributable to the excellent aeration/mechanical turbulence associated with the stream's high gradient character. Not surprisingly, DO levels were generally lower below wet BMP facilities. This was due to a combination of higher associated water temperatures and higher biochemical oxygen demand (BOD). Average surface DO levels in the Countryside wet pond were an excellent 10.9 mg/L. In addition, because of the generally larger volume of flow, hence higher stream velocity and aeration, no reduction in DO levels were observed under stormflow discharge conditions.

Out of a total of 781 measurements taken, 14 readings (1.8 percent) violated the 6.0 mg/L MDE Class III/IV dissolved oxygen standard. Another 11 readings (representing 1.4 percent of the total) violated the 5.0 mg/L MDE Class I dissolved oxygen standard. As seen in Table 17, 13 out of the 14 Class III/IV violations and 10 out of the 11 Class I violations occurred within the Oaksprings wetland-tributary system. The only other observed MDE Class III/IV violation occurred downstream of the Countryside pond. One MDE Class I violation (DO concentration of 4.2 mg/L) was also recorded immediately upstream of the Tanglewood ED pond's riser.

Oaksprings

Almost half of the observed DO standard violations (12) occurred within the Oaksprings wetland. In addition, the study's lowest DO concentration (3.9 mg/L) was recorded a short distance upstream of the wetland's riser. Throughout the monitoring period, the wetland's average DO levels were consistently lower than those recorded at other sites. The principal causal factor behind this appears to have been the large amount of decaying organic material trapped within the wetland's extensive emergent and submerged aquatic plant beds.

Table 17 Summary: Dissolved Oxygen Monitoring Results June-October, 1989

LOCATION	STATION NUMBER	MDE Water Use Class	DO(mg/l) MAX	MIN	MEAN	Sample Size	No. of Violations Cl.I std (5.0mg/l	Cl.III&IV (6.0mg/l)
1)Lakemont Trib.	1	IV	11.8	9.5	10.8	14	0	0
2)a)Oaksprings Inflow	1	III	10.4	4.9	8.5	20	1	1
ED wetland	all	III	12.5	3.9	7.2	40	6	6
outflow	1	III	10.0	5.3	7.6	19	0	2
	2	III	9.5	4.8	7.2	19	1	2
	3	III	8.9	6.0	7.4	20	0	1
	4	III	9.8	3.8	7.4	19	2	1
b)Upper Gum Springs	1A	III	11.8	9.0	10.3	20	0	0
c)Gum Springs	1B	III	13.0	8.9	10.3	20	0	0
	2B	III	11.6	8.2	9.7	15	0	0
	3B	III	11.8	9.1	10.3	19	0	0
	4B	III	11.8	8.1	9.8	19	0	0
	5B	III	11.8	8.7	10.1	19	0	0
d)Lower Gum Springs	1C	III	12.2	8.4	10.3	20	0	0
	2C	III	11.8	9.5	10.5	13	0	0
e)Paint Branch above Gum Springs	3C	III	11.9	9.1	10.4	13	0	0
below Gum Springs	4C	III	12.0	9.3	10.3	13	0	0
3)a)Countryside inflow	1	III	10.8	6.8	9.2	19	0	0
pond	all	III	20.0	6.5	10.9	56	0	0
outflow	1	III	13.5	7.1	9.4	18	0	0
	2	III	9.5	6.2	7.9	17	0	0
	3	III	10.4	5.5	8.1	19	0	1
	4	III	10.4	6.5	8.1	15	0	0
	5	III	11.4	7.1	8.3	15	0	0
	6	III	10.6	6.8	8.6	15	0	0
b)Paint Branch above Countryside	7	III	12.0	9.4	10.2	15	0	0
below Countryside	8	III	11.4	9.1	10.0	15	0	0

Table 17 cont'd:

LOCATION	STATION NO.	MDE CLASS	DO MAX	DO MIN	DO MEAN	SAMPLE SIZE	VIOLATIONS I std	VIOLATIONS III&IV
4) a) Tanglewood Inflow	1	I	10.8	7.4	8.9	15	0	0
ED Dry Pond	all	I	14.3	4.2	9.1	34	1	0
Outflow	1	I	15.3	6.8	9.1	13	0	0
	2	I	10.4	6.7	8.7	15	0	0
	3	I	11.2	7.4	9.0	13	0	0
	4	I	11.4	8.7	9.6	10	0	0
b) Auto Park Br. above Tanglewood	5	I	10.8	8.8	9.4	10	0	0
below Tanglewood	6	I	11.4	8.8	9.6	10	0	0
5) a) Fairland Ridge inflow	1	III	10.8	7.7	9.2	15	0	0
outflow	1	III	12.2	6.5	9.4	12	0	0
	2	III	11.0	7.8	9.0	15	0	0
b) Good Hope Trib. above Fairland Ridge	3	III	11.8	8.2	10.4	14	0	0
below Fairland Ridge	4	III	11.8	8.4	10.1	14	0	0
6) a) Upper White Oak	1	III	10.5	6.5	8.8	15	0	0
	2	III	10.3	7.4	8.7	7	0	0
	3	III	10.8	7.2	8.7	7	0	0
	4	III	11.6	6.7	9.6	4	0	0
	5	III	9.6	6.5	8.4	4	0	0
b) Lower White Oak	1	III	11.6	8.5	10.2	6	0	0
	2	III	10.9	7.8	9.5	14	0	0
	3	III	11.5	9.3	10.6	4	0	0
c) Paint Branch above White Oak trib	4	III	12.4	9.6	11.0	7	0	0
below White Oak trib	5	III	12.9	9.9	11.3	7	0	0
					TOTAL	781	11	14

TOTAL NUMBER OF CLASS I, III, &IV VIOLATIONS= 25

Of all the stream areas sampled, the Lower Oaksprings tributary consistently had the lowest DO levels. Average dissolved oxygen concentrations in the 500 foot long stream reach ranged between 7.2 and 7.6 mg/L. These concentrations were typically 1.0 mg/L less than the Oaksprings inflow station, and are reflective of both warmer stream temperatures and the wetland's oxygen demand on the receiving stream system. Downstream DO levels generally improved, as a result of recreation/mechanical turbulence, within 200-500 feet of the wetland. Results further showed that the Oaksprings tributary had no discernible effect on DO levels in the larger Gum Springs tributary (located 500 feet downstream of the wetland).

Summary

Results from the dissolved oxygen monitoring portion of the study revealed the following:

1. Baseflow DO levels generally do not appear to be a problem in urban streams; even in those draining highly impervious watersheds.

2. Some oxygen depletion was noted within the artificial wetland, as well as, downstream of both it and the wet pond. However, no anoxia was evident.

3. DO levels recovered within relatively short distances of the wet BMP's; generally, within 200 - 500 feet.

4. No discernible DO sag was observed during stormflow conditions.

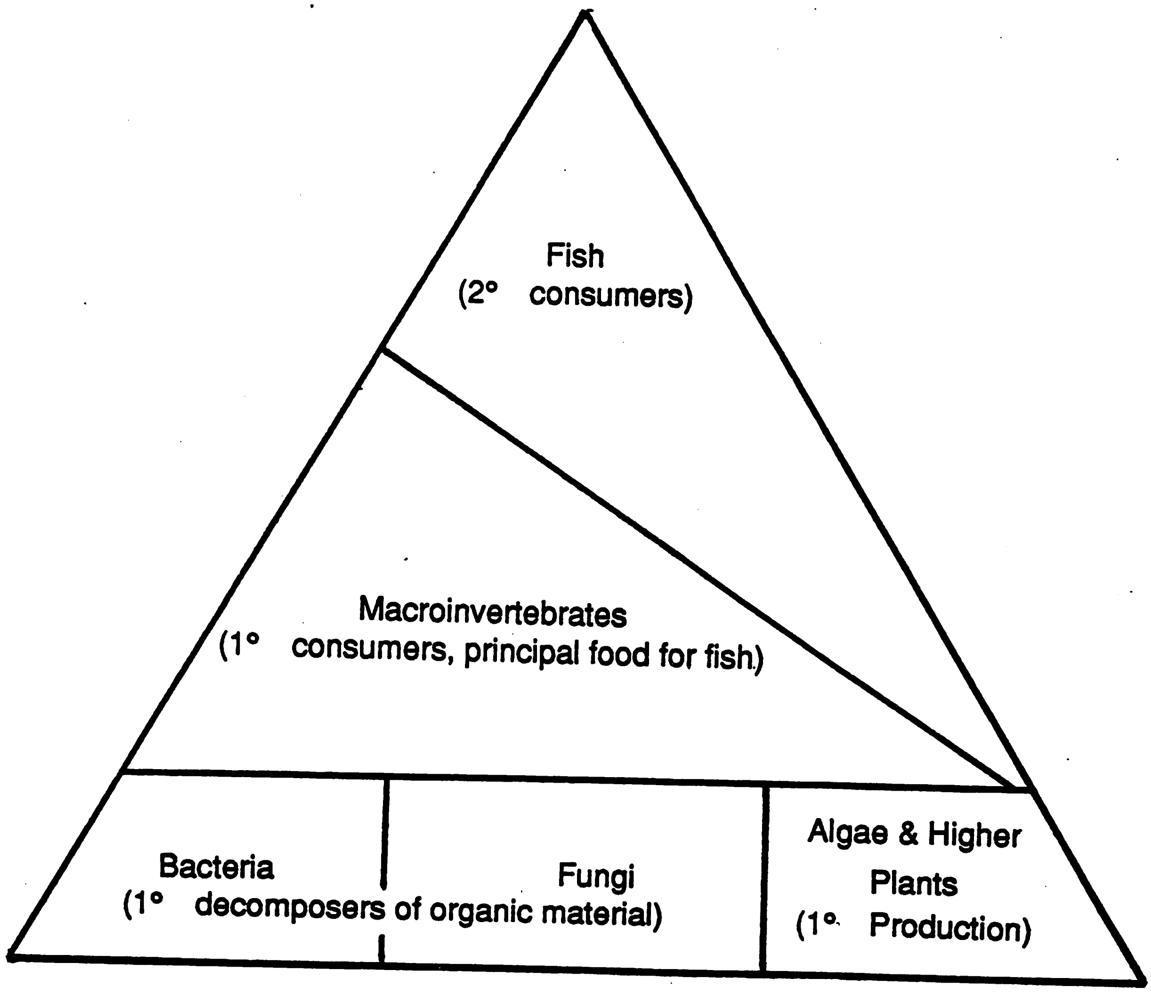
Chapter III. Water Temperature - Biological Implications

This chapter represents a synthesis of major findings from both the water temperature monitoring and literature review portions of the study. Wherever possible, an attempt was made to relate monitoring results to potential effects on biota known or expected to occur in Maryland freshwater streams. In order to accomplish this objective, a holistic approach which examined the general temperature requirements of representative biological groups at all major levels of the aquatic food chain was used. Results are presented in a sequential manner, starting at the bottom of the food chain (Figure 38) with algae, and progressing to fish.

Because of the general controversy surrounding watershed urbanization and trout streams, a separate sub-section on trout (which also contains temperature monitoring results from the Gum Springs tributary area) has been included. For a more comprehensive overview of water temperature and stream biota the reader is referred to Appendix C. In addition, because of the absence of comprehensive, stream-specific biological data, the biological implications described herein should be viewed with a certain degree of caution.

FIGURE 38

Conceptual Food Chain for Freshwater Ecosystems



1. Algae: General Temperature and Light Requirements

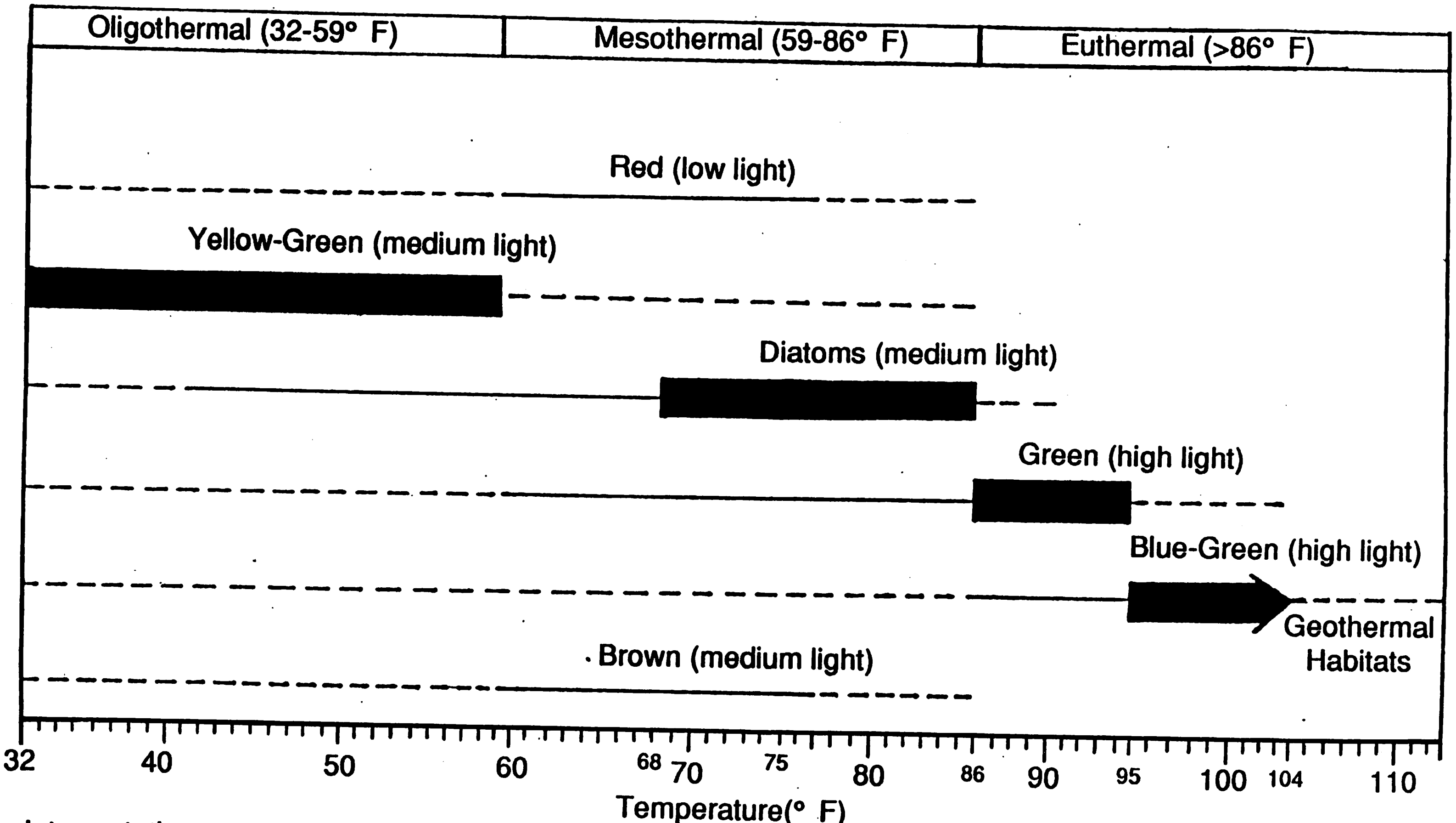
Light, water temperature, and flow are generally considered to be the primary factors regulating algal communities (Patrick, 1977). Most freshwater algae cannot grow at very low light intensities and appear to also be inhibited by high light intensity (Whitford & Schumacher, 1968). In addition, "every species of algae has a range of temperature tolerance, which is generally fairly wide, and a narrower range, typically near the upper end of the tolerance range in which optimum growth occurs" (Patrick, 1974).

The general temperature and light requirements and classification of the major groups of freshwater algae are summarized in Figure 39. As seen in Figure 39, oligothermal algae are coldwater forms which are generally restricted to waters ranging between 32 and 59^{o}F. Mesothermal algae inhabit cool-warm temperature habitats between 59 and 86^{o}F. The euthermal algae, which are characteristically warmwater forms, exhibit their greatest abundance at temperatures $\geq$ 86^{o}F.

As a rule, diatoms dominate at temperatures between 68 - 86^{o}F, green algae dominate between 86 and 95^{o}F and blue-green algae dominate in waters $\geq$ 95^{o}F (Patrick 1974). It is also important to note that, in most streams, diatoms are the overall dominant algal group. Red, brown and yellow-green algae typically comprise a relatively small portion of the stream algal community. Yellow-green algae are the dominant low temperature group (Whitford & Schumacher, 1986). They are typically restricted to cold streams and/or where present in warmer streams, to winter months.

Figure 39

Summary: General Temperature and Light Requirements and Classification of Major Algal Groups



Interpretation

—— = Greatest number of representative species
– – – = Upper and lower temperature limits
■ = Temperature range in which group is dominant
Oligothermal = Cold water forms, generally occuring between 32-59° F
Mesothermal = Temperate water forms, generally occuring between 59-86° F
Euthermal = Warm water forms, generally occuring at temperatures >86° F

Low Light = 200 foot candles
Medium Light = 500-1000 foot candles
High Light = >1000 foot candles

Thermal Enrichment

In a study of the algae of White Clay Creek, PA, Patrick (1971) found that water temperatures averaging 86.7°F caused a major shift from a diatom-dominated community to one dominated by a mixture of greens, diatoms and blue-greens. Galli (1988) observed minor shifts in diatom community composition, as well as, an increase in both green and blue-green algae downstream of a small stormwater management wet pond. Maximum summer stream temperatures below this pond were in the 77.0 to 84.9°F range. Wilde and Tilly (1981), who conducted experiments on algal communities in artificial streams, concluded that sustained Delta-T increases of between 9.0 - 13.5°F (above ambient stream temperatures) may be sufficient to cause a significant species composition shift in a stream's algal community. In most streams, temperature shifts towards the upper limit and beyond brings about a shift in species composition; generally from diatom-dominated communities to those dominated by blue-green algae.

Temperature Monitoring Assessment

A review of water temperature monitoring results suggests that subtle shifts in the periphyton (attached algae) community species composition would have been expected to have occurred in some of the urban streams studied. At all developed watershed and BMP sites' diatoms would have continued to remain the dominant overall algal group. However, certain coldwater and/or light sensitive species may have either declined in numbers and/or been replaced by other, more temperature or light-tolerant species.

The scenario would most likely have occurred in stream reaches where considerable thermal enrichment and/or removal of riparian vegetation took place (e.g., Countryside outflow, Lower Oaksprings, White Oak tributary, and Tanglewood tributary). Also, it would be expected that green and blue-green algal species would have been represented in greater numbers in the warmer, open-lit sections of these streams.

While some temperature-related shifts in algal community species composition undoubtedly occurred, it is unlikely that they would have in themselves had an appreciable effect on either the macroinvertebrate or fish communities of these small urban streams. The principal reasons for this are: 1.) from an energy or food utilization perspective, the macroinvertebrate communities of eastern headwater streams are heavily dependant upon leaf litter. Macroinvertebrates which rely largely upon attached algae (periphyton) for a food source, generally comprise a small portion of this community and 2.) by in large, macroinvertebrates, not algae, are the principal food for fish inhabiting these headwater streams.

2. Macroinvertebrates: General Temperature Requirements of Aquatic Insects

Macroinvertebrates are frequently defined as animals without backbones that are large enough to be retained on a U.S. standard No. 30 sieve, 0.595 mm openings (Weber, 1973). In addition to serving as a major food source for fish, macroinvertebrates are an integral part of the normal energy/organic material processing system of streams. Aquatic insects, which in most environments comprise the largest portion of this heterogeneous group, were examined in the study. General findings are described below.

Temperature - Physiological Relationships

As a group, aquatic insects demonstrate little ability to acclimate or compensate for temperature changes. Thus, when exposed to a new thermal regime, metabolic response is immediate and in the direction of the temperature change (Trapp & Hendricks, 1983).

While many aquatic insects can successfully complete their life cycles over a broad range of temperature conditions, many have very narrow and/or specific temperature requirements. As such, even relatively small temperature regime changes may have serious implications. For example, Sweeny and Vannote (1978) observed that changes of only 2.8 - 3.6°F, either warmer or cooler, from the normal temperature regime can reduce adult insect size and fecundity (the ability to produce viable off-spring), they both suggested that temperature increases of 3.6 - 5.4°F could eliminate sensitive species. Limited data also suggests that aquatic insects are adversely affected by exposure to high shock temperatures which approach their upper lethal limit. Thermal shocks may also interfere with the normal molting process and hence, may negatively effect insect growth and long-term survivability.

Temperature Requirements of Key Insect Groups

In general, water temperatures greater than 63.0°F have often been considered to be above the optimum for many stoneflies, mayflies, and caddisflies, and temperatures exceeding 70.0°F have been shown to stress severely most coldwater organisms (Gaufin and Nebeker, 1973; Ward and Stanford, 1979; Fraley, 1979).

As a group, stoneflies are the least temperature tolerant and are generally restricted to cold-cool flowing waters. Conversely, dragonflies and damselflies are generally associated with warmer streams and/or lakes and ponds. Mayflies and caddisflies, as well as Diptera (flies & midges), display considerable adaptivity and have successfully invaded all three of the major aquatic habitats depicted in Figure 40.

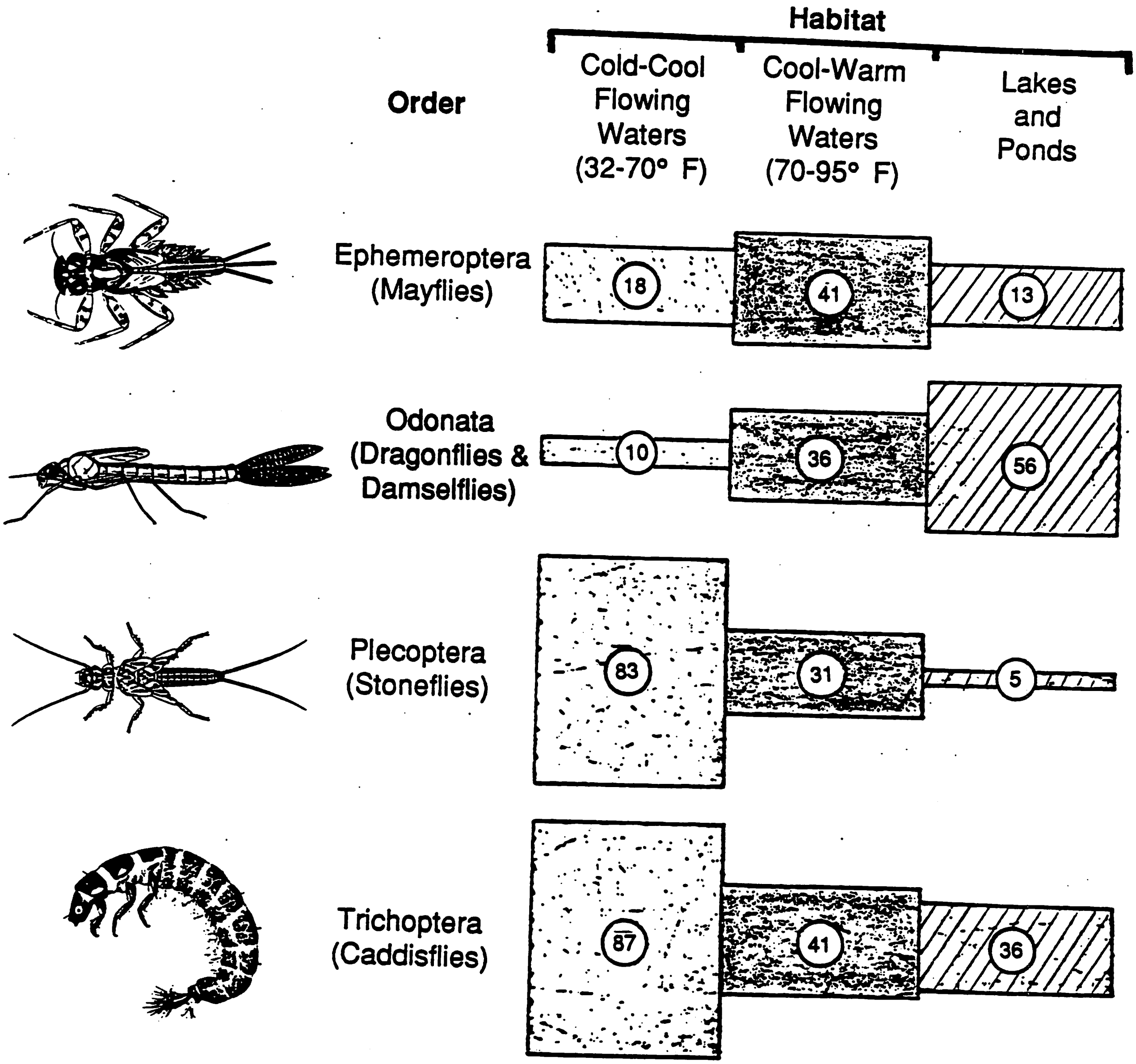
In addition, as a result of temperature regime alteration, mayflies, stoneflies, and other temperature sensitive or thermally-cued invertebrates are often reduced or eliminated below impoundments (Petts, 1984; Ward and Stanford, 1979; Fraley, 1979; Kondratieff and Voshell, 1981). All too frequently, only those forms with broad tolerance levels exist. Macroinvertebrate groups without aerial adults, such as snails, oligochaetes, amphipods, isopods, and turbellarians often increase in relative abundance in these streams (Ward and Stanford, 1979).

Temperature Monitoring Assessment

Results indicate that the thermal enrichment effects produced either through urbanization and/or associated BMP's, would severely effect coldwater aquatic insects. As seen in Figure 41, it is most likely that sensitive groups, such as stoneflies, would either be eliminated or severely restricted (for much of the year) at temperature levels comparable to those

Figure 40

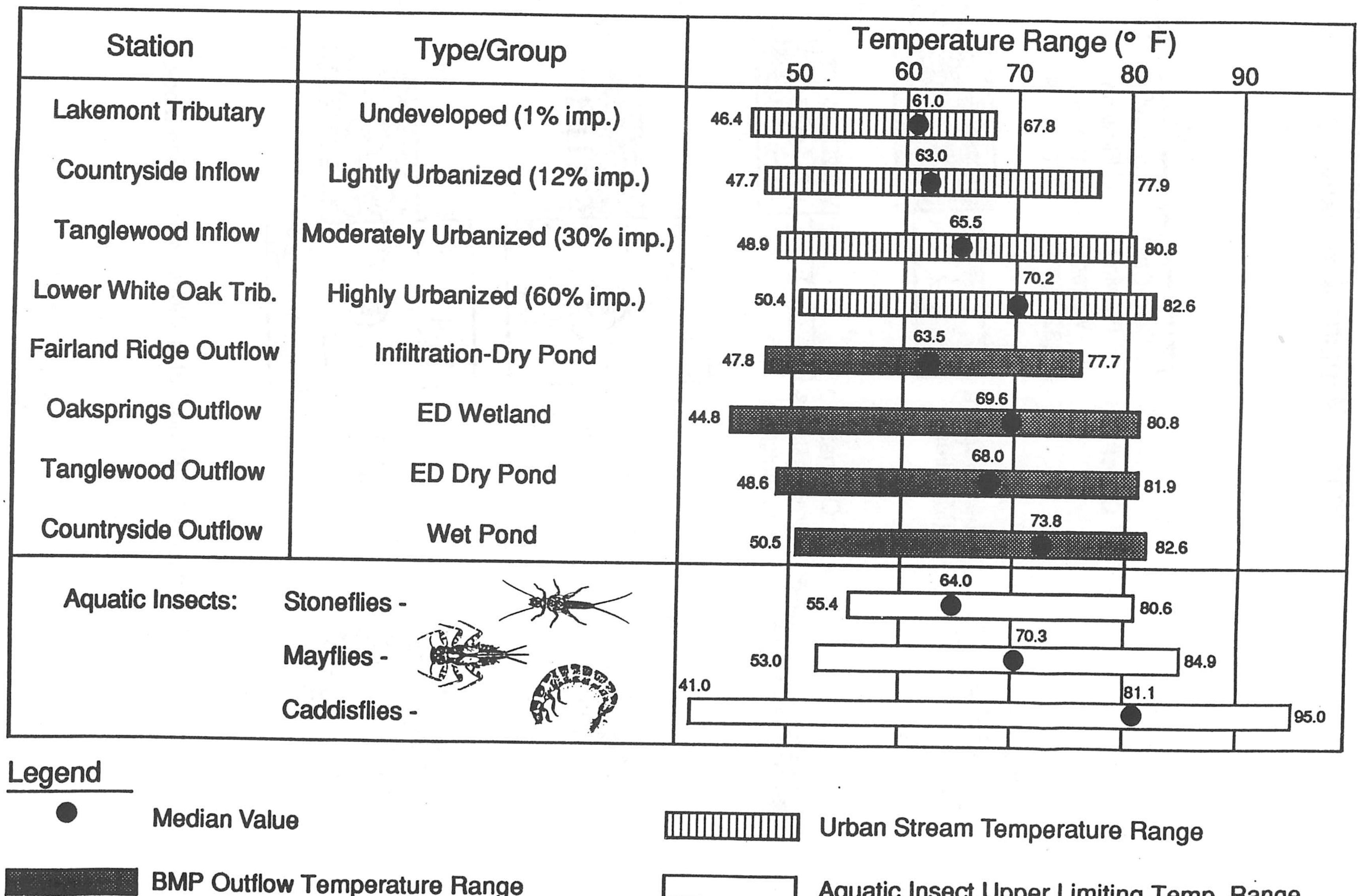
General Habitat of Four Orders of North American Aquatic Insects [1/]
(modified from Wiggins & Mackay, 1978)



1/ Number of genera per habitat is shown within each block.

FIGURE 41

GENERAL RELATIONSHIP BETWEEN URBANIZATION, BMP'S, AND UPPER LIMITING TEMPERATURES FOR KEY AQUATIC INSECT GROUPS[1/]



1/ Upper limiting temperature defined as temperature above which death is extremely likely.

observed at the moderately and highly developed watershed sites and at the wet pond, ED wetland, and ED dry pond outflow stations. While collectively more temperature tolerant, many mayfly and caddisfly species would similarly be eliminated, severely restricted and/or stressed at the preceding temperature levels.

Consequently, restructuring of the macroinvertebrate community would occur, with intolerant species and/or groups of insects being replaced by thermally-tolerant ones. It would also be expected that tolerant groups such as Diptera (flies & midges) would gain greater dominance in these stream systems. In addition, non-insect species would probably become more abundant. The preceding changes could, if particularly extensive, have a negative impact on the resident fish community.

3. Fish: General Temperature Requirements, Classification and Tolerance

Although fish may be found in waters with temperatures ranging from around *zero to* 111.0^{o}F, no species can survive over this entire range. Each species has a characteristic range with upper and lower lethal limits and preferred temperature optima, which changes according to the age (or life cycle stage) of the fish. Furthermore, when water temperature changes, the rate of thermal equilibration in fish is generally rapid (Elliot, in Pickering, 1981). Owing to their smaller body mass and proportionately higher surface area, juveniles are far more vulnerable to the effect of rapid temperature changes than are adult fish.

Temperature Classification

Freshwater fish in temperate regions generally live within the 32.0 - 86.0^{o}F temperature range. Maximum summer temperatures may exceed 86^{o}F in shallow lakes, ponds and marshes, warmer southern streams, and/or in waters that receive a thermal discharge. Based on their thermal requirements, fish are generally placed into one of three categories:

- Stenotherm - coldwater fish, which have a physiological optimum $< 68^{o}$F and an upper lethal temperature of $< 79^{o}$F. Representative examples include salmon, trout, and certain sculpins.

- Mesotherm - coolwater fish, which have a physiological optimum in the 68 - 84.4^{o}F range and an upper lethal temperature of 82.4 - 93^{o}F. Representative examples include pikes, perch, darters, and most species of minnows.

- Eurytherm - Warmwater fish, which have a physiological optimum > 82.4^{o}F and an upper lethal temperature generally over 93^{o}F. Representative examples include carp, goldfish, catfish, sunfish, and bass.

General Temperature Requirements of Maryland Freshwater Fish

Water temperature together with the volume of flow, water quality, and physical or structural habitat are the major factors which determine the fish community characteristics of streams. While it was beyond the scope of the study to examine all of these variables, an attempt was made to identify the general temperature requirements for Maryland freshwater fish. Thermal requirement data for 63 species of fish known or expected to occur in Maryland freshwater streams is presented in Appendix C. In addition, this information together with water temperature monitoring results have been graphically summarized in Figure 42.

The upper and lower critical temperature limits depicted in Figure 42 represent reasonably well-defined physiological temperature boundaries, beyond which, death is extremely likely. Also, temperatures outside of the optimum range may generally be viewed as being stressful. Finally, it is

Figure 42

General Temperature Requirements of Maryland Freshwater Fish Versus Maximum Observed BMP Outflow Temperatures

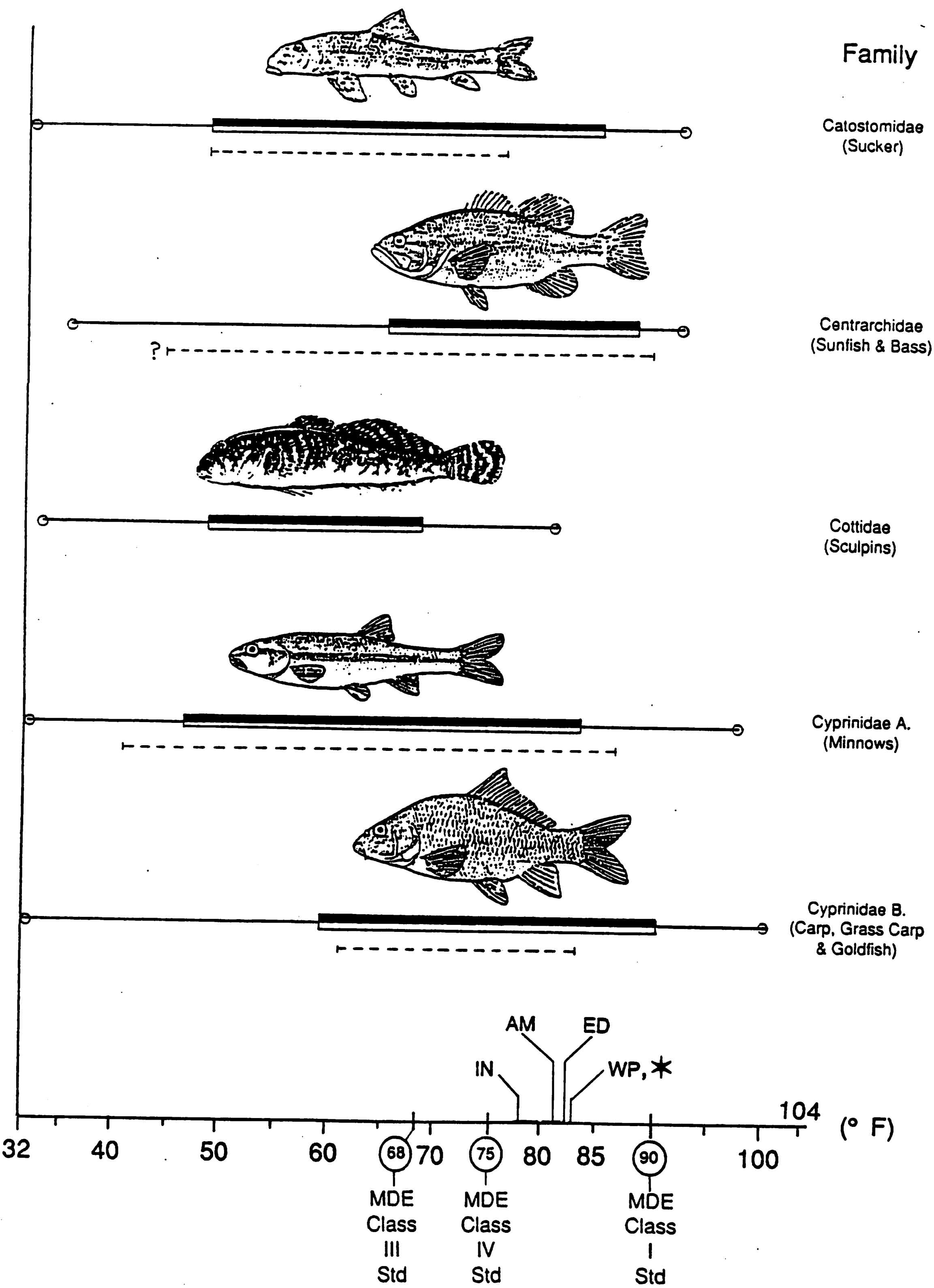
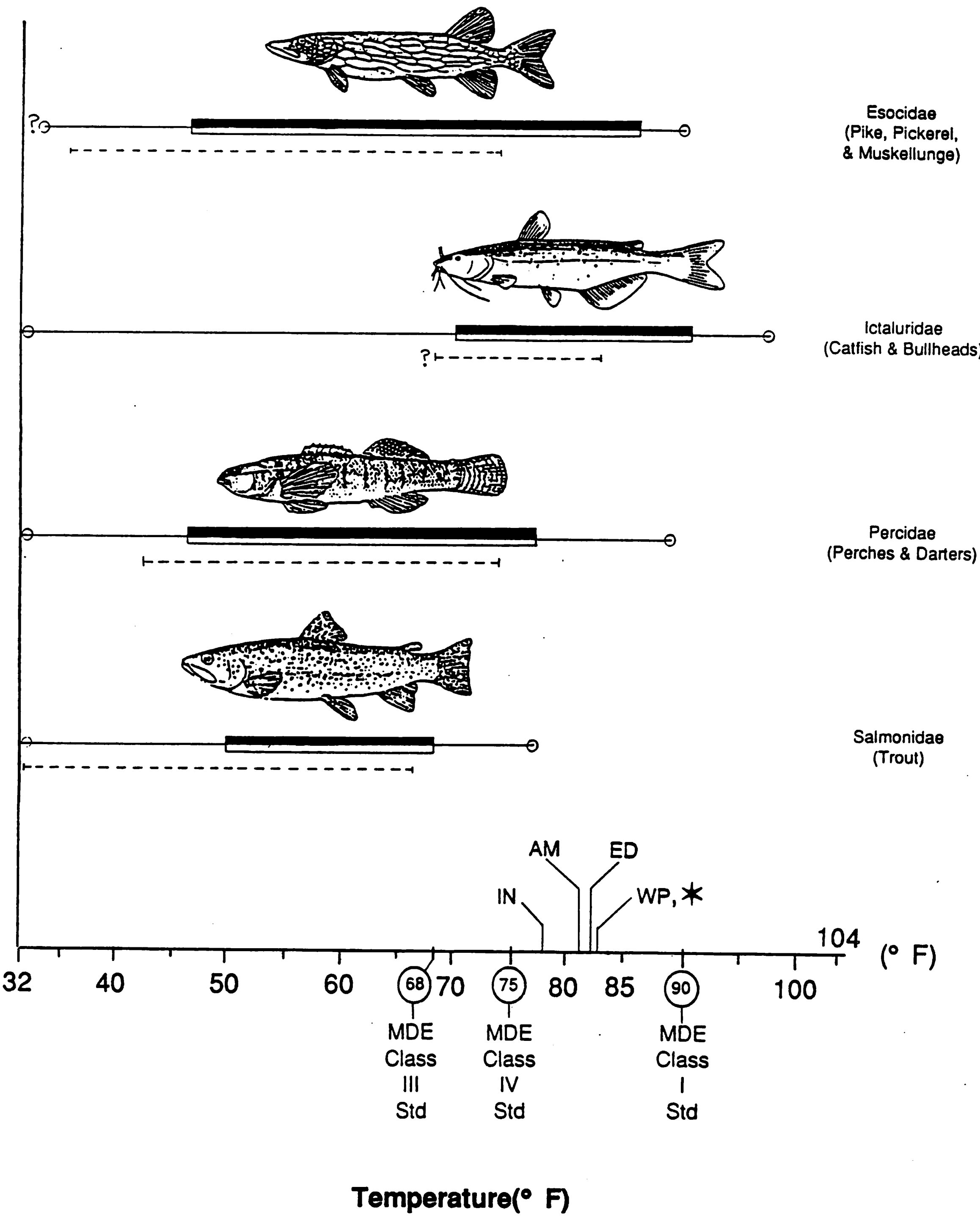


Figure 42 (cont)



Legend

- Upper and lower critical temperature limits
- General optimum temperature range
- Temperature limits for egg development

IN - Fairland Ridge Infiltration Dry Pond (77.7° F)

AM - Oaksprings Artificial Marsh (80.8° F)

ED - Tanglewood Extended Detention Dry Pond (81.9° F)

WP - Countryside Wet Pond (82.6° F)

* - Lower White Oak Trib., 60% impervious, (82.6° F)

important to note that a fish's ability to withstand thermal stress is largely a function of acclimation temperature, its age and vigor, and length of exposure.

Temperature Monitoring Assessment

Results presented in Figure 42 show that the vast majority of fish species would not be affected by the temperature increases produced either through urbanization and/or construction of BMP's. However, coldwater species such as trout would not be expected to survive at temperature levels observed at either the moderately or highly developed watershed sites or at any of the four BMP outflow locations. While generally regarded as being slightly more temperature tolerant than trout, sculpins would also be negatively impacted. As seen in Figure 42, sculpins would only be expected to survive at temperature levels observed at either the lightly developed watershed sites, or below the infiltration - dry pond.

The preceding findings underscore the point that moderate levels of watershed imperviousness and/or the improper introduction of BMP's, can have a devastating impact on sensitive coldwater streams and the fish communities which they support.

4. Trout and Thermal Stress

A. General Findings

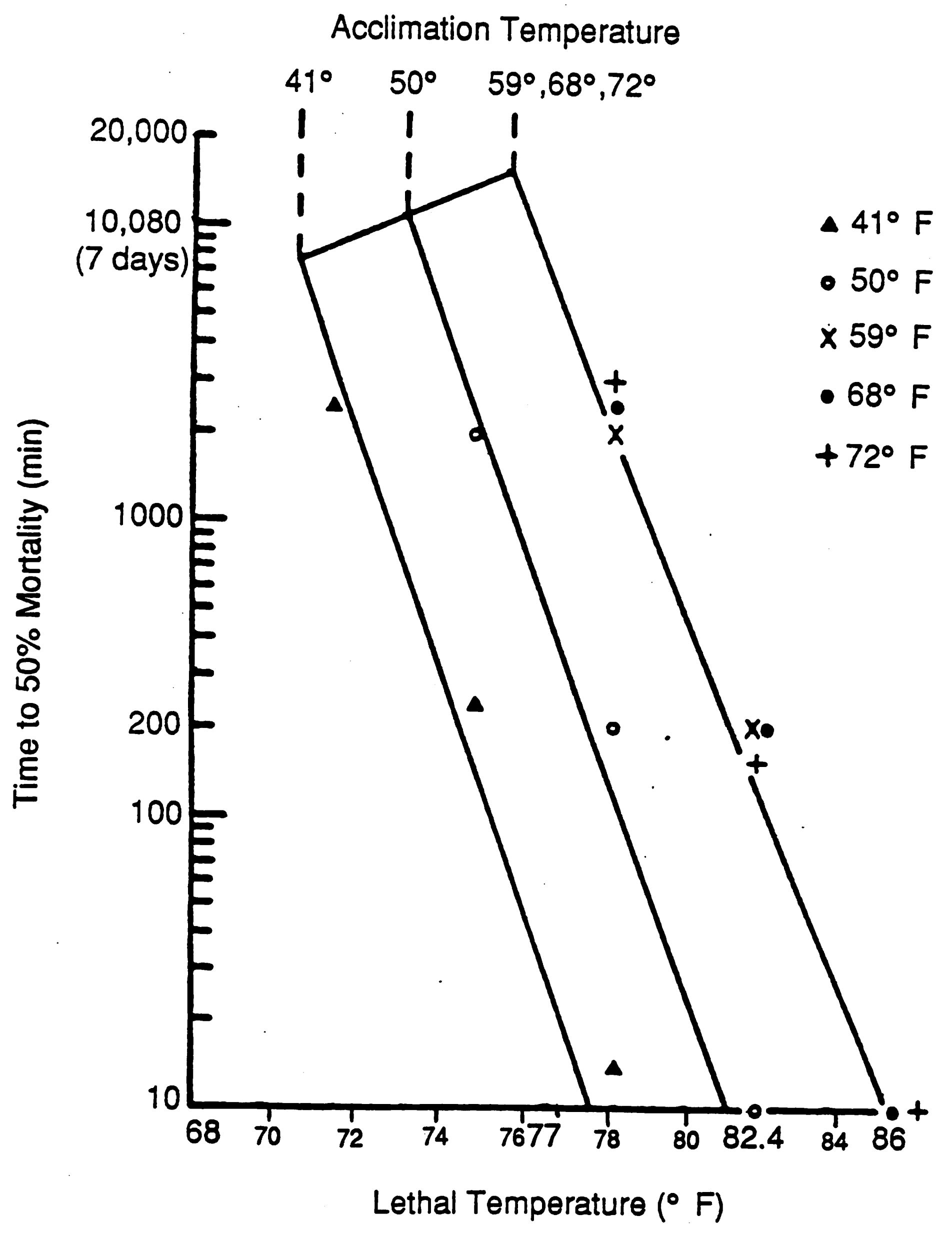
With only one or two notable exceptions, natural coldwater stream fish communities in Maryland are generally restricted to higher altitude and/or spring-fed streams of the Appalachian and Piedmont provinces. The fish assemblage in these streams is often highly variable, but typically includes one or more species of trout (brook, and/or brown or rainbow), as well as, sculpins, and several minnow species. Maximum summer water temperatures in coldwater streams are normally less than 70°F (Winger, in Krumholz, 1981).

While the temperature requirements for brook, brown and rainbow trout are quite similar, the brown trout is generally regarded as being the more temperature tolerant and the brook trout the least. It is important to note that even within a given species the difference in thermal tolerance is often surprisingly large. Much of this is due to inherent genetic or racial differences within the species and adaptation to different thermal regimes.

All trout species are extremely sensitive to thermal pollution/stress. Sustained elevated water temperatures over 70°F are generally considered to be stressful, while those at or above 77°F are usually lethal. As previously noted, a fish's ability to withstand or resist the effects of thermal stress is heavily influenced by the acclimation temperature. Trout can, depending on the acclimation temperature, survive for varying periods of time at temperatures which are ultimately lethal. As seen in Figure 43, brown trout

Figure 43

Relationship Between Time, Acclimation Temperature and 50% Mortality of Brown Trout, Salmo trutta (from Elliot, 1981)



acclimated at 59, 68, or 72°F survived slightly over 7 days at 77°F, 100 minutes at 82.4°F, and only 10 minutes at 86°F.

B. Gum Springs Thermal Regime

From a historical perspective, the Gum Springs tributary has supported a naturally reproducing brown trout population since at least the mid-1950's. During the past 10 - 12 years the Gum Springs tributary subwatershed has experienced considerable watershed development activity. Presently, this residentially developed basin, which includes the Oaksprings ED wetland - tributary system, is approximately 12 percent impervious.

Despite this background level of watershed imperviousness the Upper Gum Springs continues to support a healthy brown trout population. Unfortunately, this is no longer the case in Lower Gum Springs. Over the past 6 - 7 years, the resident trout population downstream of the Oak Springs tributary confluence has steadily declined (Gougeon, 1990). While much of this decline has been attributed to construction-related sediment pollution and increased stormflows, temperature regime alteration has been repeatedly implicated (Gougeon, 1990).

In an effort to document longitudinal thermal regime differences, thermograph thermometers were strategically located in both Upper and Lower Gum Springs. Water temperature monitoring results confirmed that under both baseflow and stormflow conditions Lower Gum Springs is warmer. They also revealed that the two stations behave very differently under large stormflow conditions. Major findings are described below.

1. While baseflow temperatures at Lower Gum Springs were typically 1 - 2°F warmer than those recorded at Upper Gum Springs, they were safely below levels considered to be stressful to trout (Figure 44).

2. Under stormflow conditions (Figure 45) both stations exceed the Class III temperature standards. Whereas only one percent of all storm events at Upper Gum Springs resulted in a temperature standard violation, 8 percent did so at Lower Gum Springs. Moreover, Lower Gum Springs stormflow temperatures reached a high of 74.5°F. This value was 3.1°F higher than the maximum stormflow temperature recorded at Upper Gum Springs.

3. The temperature regimes of both stations were generally unresponsive to runoff produced by small-medium size storm events (i.e., $\leq$ 1.0 inch of precipitation). Larger storms (those dropping $\geq$ 1.0 inches of rain), however, produced sharp temperature increases at both stations. Under these large stormwater inflow conditions, Gum Springs stream temperatures were observed to increase at rates of 4.3 - 9.7°F per hour. It should also be noted that the single largest 20 minute temperature increase, 7.2°F, occurred at the Upper Gum Springs station.

4. The principal differences between the two stations, under the large storm event scenario, were the magnitude of the temperature increase and the recovery rate. Results showed that temperature increases were higher and recovery slower at Lower Gum Springs. During these storm events, Upper Gum Springs temperatures typically remained

FIGURE 44

UPPER VERSUS LOWER GUM SPRINGS WATER TEMPERATURES UNDER BASEFLOW CONDITIONS

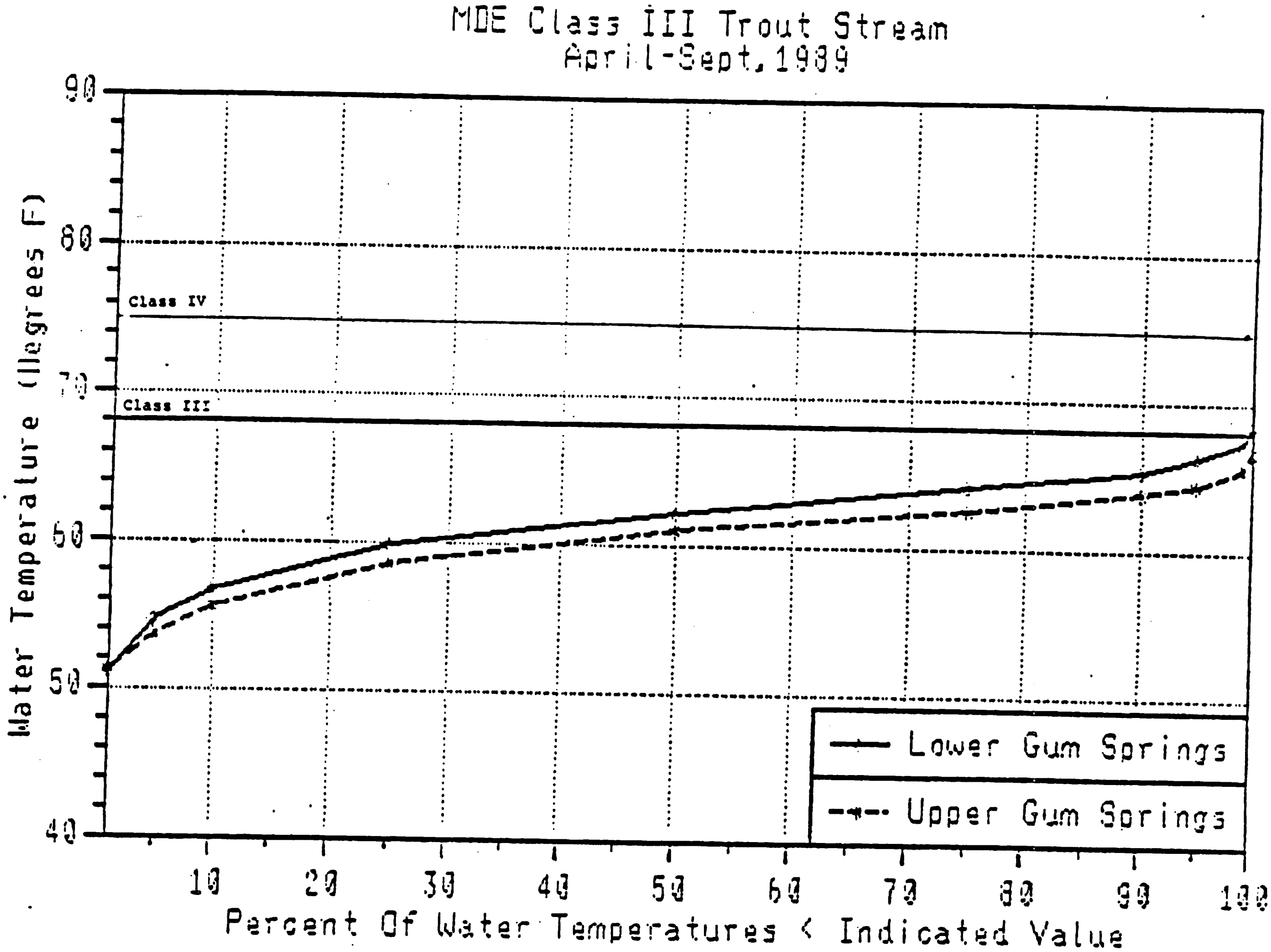
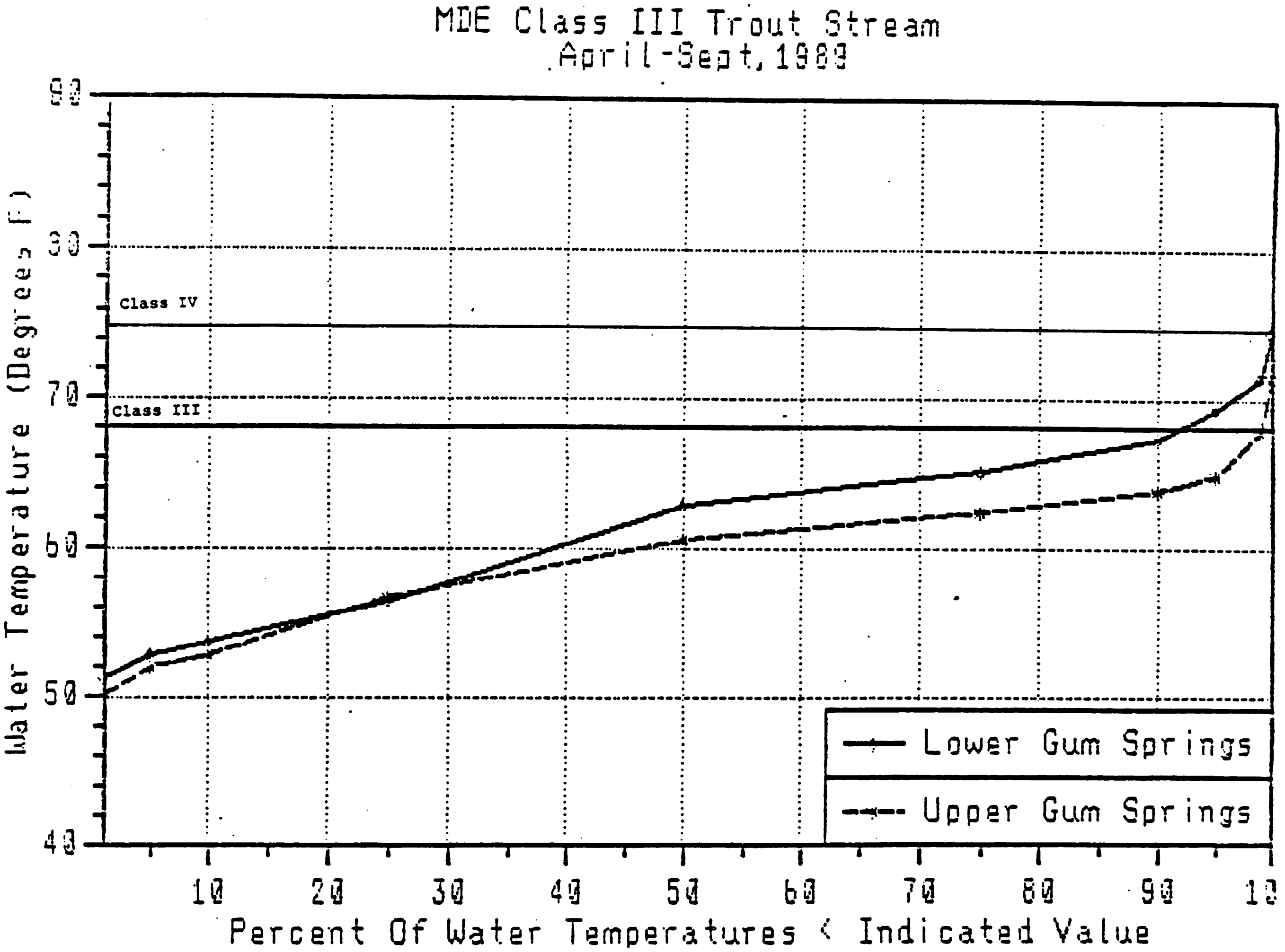


FIGURE 45

UPPER VERSUS LOWER GUM SPRINGS WATER TEMPERATURES UNDER STORMFLOW CONDITIONS



elevated for 6 - 12 hours before returning to normal. In contrast, water temperatures at Lower Gum Springs remained elevated for up to 2 - 3 days at a time. The long, Lower Gum Springs recovery period is attributable to the relatively slow release of large volumes of stormwater from the Oaksprings Ed wetland. During the study it was not unusual to see Lower Gum Springs temperatures remain at or above $70^{\circ}F$ for periods of 30 - 40 hours. As previously noted, sustained temperatures $\geq 70^{\circ}F$ are generally considered to be stressful to trout, especially young-of-year and juvenile trout, who are least tolerant of high temperatures and are first affected by thermal shock.

The preceding findings underscore the fragile nature of urban trout streams and their vulnerability to large inputs of stormwater runoff. Although the water temperature regimes of both Upper and Lower Gum Springs are still quite capable of supporting trout, the Lower Gum Springs is far more thermally stressed. It is also quite likely that additional watershed development, particularly in the headwaters, will cause further deterioration of the Gum Springs tributary thermal regime. This could conceivably result in the elimination of all trout from the stream.

Chapter IV. Land Use Control and Stormwater Management Program Implications

Through the process of urbanization, vegetation is removed from watersheds, formerly pervious surfaces are converted to hard, impermeable ones such as rooftops, streets and parking lots, and natural drainage networks are modified to convey runoff more efficiently. These processes act together to alter the thermal regime of urban, headwater streams. The extent to which the thermal regime of these streams is modified is largely a function of three major interrelated factors: 1.) watershed imperviousness levels, 2.) integrity of riparian canopy coverage, and 3.) the employment of stormwater BMP's. These factors, as related to land use and stormwater management control programs, are discussed in greater detail in the following sections.

Land Use Control Implications

1. Watershed Imperviousness Factor

For urban headwater streams, the level of watershed imperviousness largely determines the magnitude of change from the pre-development thermal regime. Results from this study show that a linear relationship exists between the level of imperviousness and mean, summer stream temperatures. In general, the mean summer water temperature of these streams will increase $0.14^{o}F$ per one percent increase in watershed imperviousness. Other important findings are described below:

- Watershed imperviousness has a negative influence on stream temperatures under both baseflow and stormflow conditions. As seen in Table 18, the frequency of MDE temperature standards violations generally increases with increasing levels of imperviousness. This phenomenon occurs regardless of whether watershed stormwater management controls are present or absent. Reduction of groundwater flows, the urban heat island effect, removal of riparian vegetation, and drainage network alteration are primary causes of the problem;

- As the level of watershed imperviousness increases, the ratio of stormwater runoff to receiving stream flow increases. Consequently, the potential for large inputs of biologically harmful warm stormwater to urban stream increases. Because small urban streams have relatively low volumes of baseflow discharge, these streams are most susceptible to the effects of thermal loading;

- With increasing watershed imperviousness, the rainfall volume required to produce large storm temperature fluctuations decreases. As previously noted, at a 12 percent watershed imperviousness level over 0.7 inches of rainfall is generally required to produce a temperature "spike." Conversely, at a 60 percent imperviousness level, less than 0.2 inches of rainfall are needed to produce a comparable temperature spike.

Table 18. Summary: MDE Water Temperature Standards Violations Versus Watershed Imperviousness

Watershed Development Level	Percent Imperviousness (%)	Percent of Time MDE Temperature Std. Violated (%)			
		Class III (68°F)		Class IV (75°F)	
		Baseflow	Stormflow	Baseflow	Stormflow
Light	12.0	10	5	0	1
Moderate	30.0	25	1	25	1
High	60.0	67	57	12	10

2. Riparian Vegetation Removal Factor

Riparian vegetation plays a key role in insulating small streams from the warming effect of solar radiation. Other studies have shown that the removal of riparian vegetation can raise the summer water temperature of small streams by 11 - 20°F, and can lower winter water temperatures by 5 - 7°F. Results from this study revealed an average positive stream Delta-T of 1.5°F per 100 feet of flow through either open or poorly-shaded reaches.

The need for maintaining vegetated riparian buffers is critical for the protection of thermal regime in urban headwater streams; and particularly so, for trout streams.

3. Conflicting Stream Protection and Watershed Development Goals

All too often the goal of stream protection conflicts with land use development. Many of the environmental problems caused by urbanization, stream warming for one, cannot be completely mitigated by engineering means. Thus, far greater emphasis on land use control measures is required in sensitive streams.

Results from this study show that stream temperature regime changes occur at relatively low levels of watershed imperviousness (i.e., $\leq$ 12 percent). They also strongly suggest that trout and other coldwater biota will most likely be lost when watershed imperviousness exceeds 12 - 15 percent.

4. Thermal Regime Protection Strategy

Current water temperature class designations are not a reliable guide to the existing or future thermal regime status of headwater Piedmont streams. This is particularly the case for urban streams. In addition, it is clear that the long-term protection of thermally sensitive streams requires a holistic watershed management approach which includes, at a minimum, the following water temperature protection elements:

- Land use controls (which govern type, density and location of development within a watershed);
- Riparian/stream buffer requirements;
- Employment of temperature sensitive BMP's and stormwater conveyance systems;
- Long-term water temperature and biological monitoring at strategic stream locations within the watershed; and
- Routine long-term maintenance of BMP's and other associated infrastructure.

Not surprisingly, extraordinary land use, riparian management and stormwater management controls are needed to properly protect the resident aquatic life of MDE Class III streams. The same watershed protection approach is also generally needed, on a case-by-case basis for thermally sensitive Class I and IV stream areas. This stream protection strategy requires that many difficult, and potentially costly, land use decisions be made.

Stormwater Management Program Implications

Stormwater management controls are employed in an attempt to mitigate the undesirable changes in watershed hydrology, water quality and stream ecology produced by urbanization. Unfortunately, the improper employment of these BMP's can exacerbate the thermal regime problems caused by watershed development. In thermally sensitive watersheds, the selection of appropriate stormwater management controls is often a difficult decision, fraught with potential water quality/quantity and environmental trade-offs. Major stormwater management program implications are discussed below.

1. BMP Thermal Performance

As previously noted, none of the four types of stormwater BMP's monitored were thermally neutral. Of the four practices, the infiltration-dry pond produced the smallest total Delta-T increases and had the fewest MDE Class III and IV temperature standards violations. The artificial wetland was next, with intermediate total Delta-T increases and temperature standards violations. The second highest Delta-T increases were associated with the extended detention dry pond. From a temperature performance standpoint, the wet pond finished last. This BMP produced the largest Delta-T increases, maintained elevated downstream temperature conditions for months at a time, and had the highest percentage of Class III and IV temperature standard violations.

The preceding results strongly suggest that all of the major stormwater management practices commonly in use will generally amplify, to some extent, baseflow and/or stormflow Delta-T's. It is further evident that infiltration BMP's provide the greatest level of water temperature protection and are the most appropriate practice for use in thermally sensitive watersheds.

2. BMP Contribution to Stream Warming Problem

At low levels of watershed imperviousness, improper BMP selection can have a major negative effect on the water temperature regime of small, headwater Piedmont streams. This is particularly the case in coldwater stream systems, where the selection of conventional wet and/or extended detention BMP's could conceivably eliminate temperature sensitive species such as trout.

However, results from the study also show that at moderate levels of watershed imperviousness the potentially negative influence of BMP's on the receiving steam's temperature regime is reduced. This is due to the fact the temperature regime of these streams have been (or will be) modified by the background level of urbanization. Consequently, temperature sensitive biota will, even in the absence of BMP's, most likely be reduced and/or eliminated from these streams. At high levels of watershed imperviousness, the general impact of BMP's on the receiving stream temperature regime is minimal. In these streams, the need for providing high levels of water quality and stream channel erosion control may outweigh temperature concerns.

3. BMP Design Elements which contribute to Thermal Loading

During the course of the study it became obvious that several BMP design elements were actually increasing total Delta-T's. Among the top five contributing factors were:

- undersized infiltration treatment system capacity;
- the presence of a large wet pool;
- poorly shaded pilot and outflow channels;
- poorly shaded storage pool areas; and
- excessively long periods of extended detention control.

4. BMP Temperature Reduction Methods

A number of BMP design features and methods could be employed to help reduce stream warming. Methods include, but are not limited to, the following:

- increasing, to the maximum practical extent possible, infiltration system treatment capacity;

- combining both infiltration water quality control and dry water quantity control within one, single facility;

- constructing BMP's as "off-line" rather than "on-line" facilities (this would help to reduce baseflow Delta-T's);

- incorporating baseflow diversion systems into "on-line" facilities;

- heavily shading pilot and outflow channels and storage pool areas with trees and shrubs;

- Incorporating narrow-width baseflow channels into BMP outflow channel design;

- limiting the maximum period of extended detention control to 6 - 12 hours;

- employing parallel pipe conveyance systems, so as to reduce the frequency and magnitude of receiving stream thermal loading;

- employing passive and/or mechanical systems to reduce baseflow/stormflow temperatures (e.g., cooling reservoirs, cooling chambers, and multiple-port releases for deep reservoirs).

- Employing, when full infiltration controls are neither practical nor feasible, alternative BMP's such as sand filters; and

- Avoiding the use of permanent pools in thermally sensitive watershed areas that are expected to have low to moderate levels of watershed imperviousness.

Several of the preceding methods and design features are experimental in nature and may or may not work until tested under field conditions. In addition, some of these design features may actually reduce the overall level of water quality or quantity control. It is further recognized that these innovative engineering approaches cannot totally eliminate the large Delta-T increases produced by large volumes of urban runoff. Also, the ability of these innovative BMP's to function as designed is dependant upon proper construction and long-term maintenance. Last, stormwater management program research priorities should include the monitoring of parallel pipe and baseflow diversion systems, multiple-port release wet ponds, sand filters, peat-sand filters and other promising thermally sensitive conveyance systems and BMP's.

References

Elliot, J.M., 1981. Some aspects of thermal stress on freshwater teleosts. In: A.D. Pickering (ed): Stress and Fish. Academic Press, NY.

Embody, G.C., 1927. An outline of stream study and the development of a stocking policy. Contr. Aquic. Lab. Cornell Univ., 22 pp.

Fraley, J.J., 1979. Effects of elevated stream temperature below a shallow reservoir on a coldwater macroinvertebtate fauna. In: J.V. Ward and J. A. Stanford (eds): The ecology of regulated streams. Plenum Press, NY. pp. 247-272.

Galli, F.J., 1988. A limnological study of an urban stormwater management pond and stream ecosystem. Unpublished Master's Thesis, George Mason University, Fairfax, Va., 153 pp.

Gaufin, A.R. and A. V. Nebeker, 1973. Water quality requirements of aquatic insects. USEPA 6660/3-73-004.

Gougeon, C., 1990. Personal communication. Coldwater Fisheries Biologist. Maryland Dept. of Nat. Res.

Gray, J.R.A. and J.M. Edington, 1969. Effect of woodland clearance on stream temperature. J.Fish Res. Bd. Canada, 26: 399-403.

Karr, J.R. and I.J. Schlosser, 1977. Impact of nearstream vegetation and stream morphology on water quality and stream biota. USEPA, Athens, Ga. EPA - 600/3-77-097, 91 pp.

Klein, R.D., 1979. Urbanization and stream quality impairment. Water Res. bull., 15(4): 948-963.

Kumble, P.A., 1990. State of the Anacostia: 1989 Status Report. Prepared for the Anacostia Watershed Committee. Publ. No. 90702. Washington, D.C.: Metropolitan Washington Council of Governments. 61 pp.

Lynch, J.A., E.S. Corbett, and W.E. Sopper, 1980. Evaluation of management practices on the biological and chemical characteristics of stream flow from forested watersheds. Inst. Res. on Land & Water resources. The Pennsylvania State University, University Park, Pa. 98 pp.

Macan, T.T., 1958. The temperature of a small stony stream. Hydrobiologia 12: 89-106.

McPherson, E.G., 1990. Cooling urban heat islands with sustainable landscapes - Draft Manuscript. Proc. Sustainable cities symposium: preserving and restoring urban biodiversity. School of Nat. Res., Univ. of Arizona, Tucson, Az.

Patrick, R. 1971. The effects of increasing light and temperature on the structure of diatom communities. Limnol. Oceanogr., 16(2): 405-421.

__________ 1974. Effects of abnormal temperature on algal communities. In: J.W. Gibbons, and R.R. Sharitz (eds.): Thermal Ecology. Tech. Info. Ctr., U.S. Atomic Energy Commission, pp. 335-349.

__________ 1977. The biology of diatoms. In: D. Warner (eds.): Thermal Ecology. Tech. Info. Ctr., U. S. Atomic Energy Commission, pp. 335-349.

Petts, G.E., 1984. Impounded Rivers - Perspectives for ecological management. John Wiley and Sons. 326 pp.

Pluhowski, E.J., 1970. Urbanization and its effect on the temperature of the streams on Long Island, New York. U.S. Geol. Survey, Professional Paper 627-D. 110 pp.

Schueler, T.R., 1987. Controlling urban runoff: A practical manual for planning and designing urban BMPs. Prepared for the Washington Metropolitan Water Resources Planning Board. Publ. No. 87703.

Washington, D.C.: Metropolitan Washington Council of Governments. 275 pp.

Sweeney, B.W. and R.L. Vannote, 1978. Size variation and the distribution of hemimetabolous aquatic insects: two thermal equilibrium hypotheses. Science 200 (4340): 444-446.

Trap, K.E. and A.C. Hendricks, 1983. Modifications in the life history of Glossoma nigrior exposed to three different thermal regimes. Proc. 4th Int. Symp. Trichoptera, Clemson, SC, 11-16 Jul 1983, pp. 397-406

Ward, J.V. and J.A. Stanford, 1979. Ecological factors controlling stream zoobenthos with emphasis on thermal modification of regulated streams. Plenum Press, NY, pp. 35-55.

Weber, C.I., 1973. Biological field and laboratory methods for measuring the quality of surface water and effluents. Nat. Envio. Res. Cent. USEPA Cincnnat, OH. EPA - 4-73-001.

Whitford, L.A. and G. J. Schumacher, 1967. Notes on the ecology of some species of freshwater algae. Archiv. for Hydrobiol. 10: 225-235.

Wiggins, G.B. and R.J. MacKay, 1978. Some relationships between systematics and trophic ecology in Nearactic aquatic insects, with special reference to Trichoptera. Ecology 59 (6): 1211-1220.

Wilde, E.W. and L.J. Tilly, 1981. Structural characteristics of algal communities in thermally altered artificial streams. Hydrobiologia 76: 57-63.

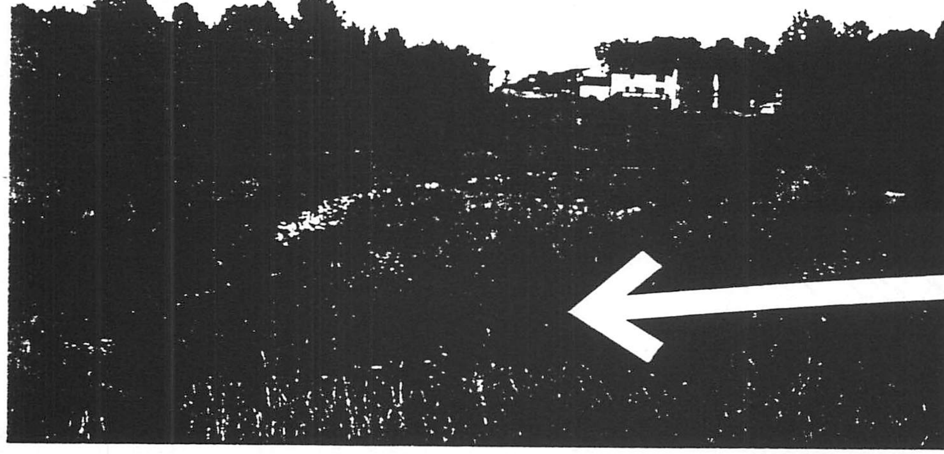
Winger, P.A., 1981. Physical and chemical characteristics of warmwater streams: A review. In: L.A. Krumholz (ed.): The warmwater streams symposium. South Div. Am. Fish. Soc, Lawrence, Ka., pp. 32-44.

Appendix A: BMP Monitoring Sites

1. Fairland Ridge Infiltration - Dry Pond

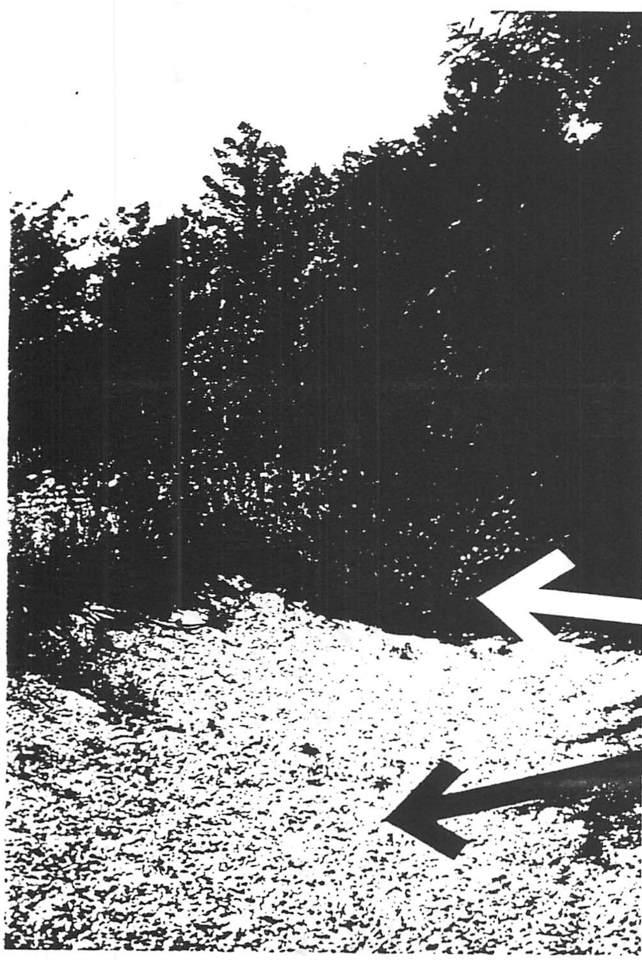
<u>Background/ Features</u>

- DA to BMP: 25.0 ac.
- Imperviousness: 18%
- Full 2-year water-quantity control
- Terraced side slopes which feature stilling basins, and 3 infiltration trenches for water quality control



Stilling basin

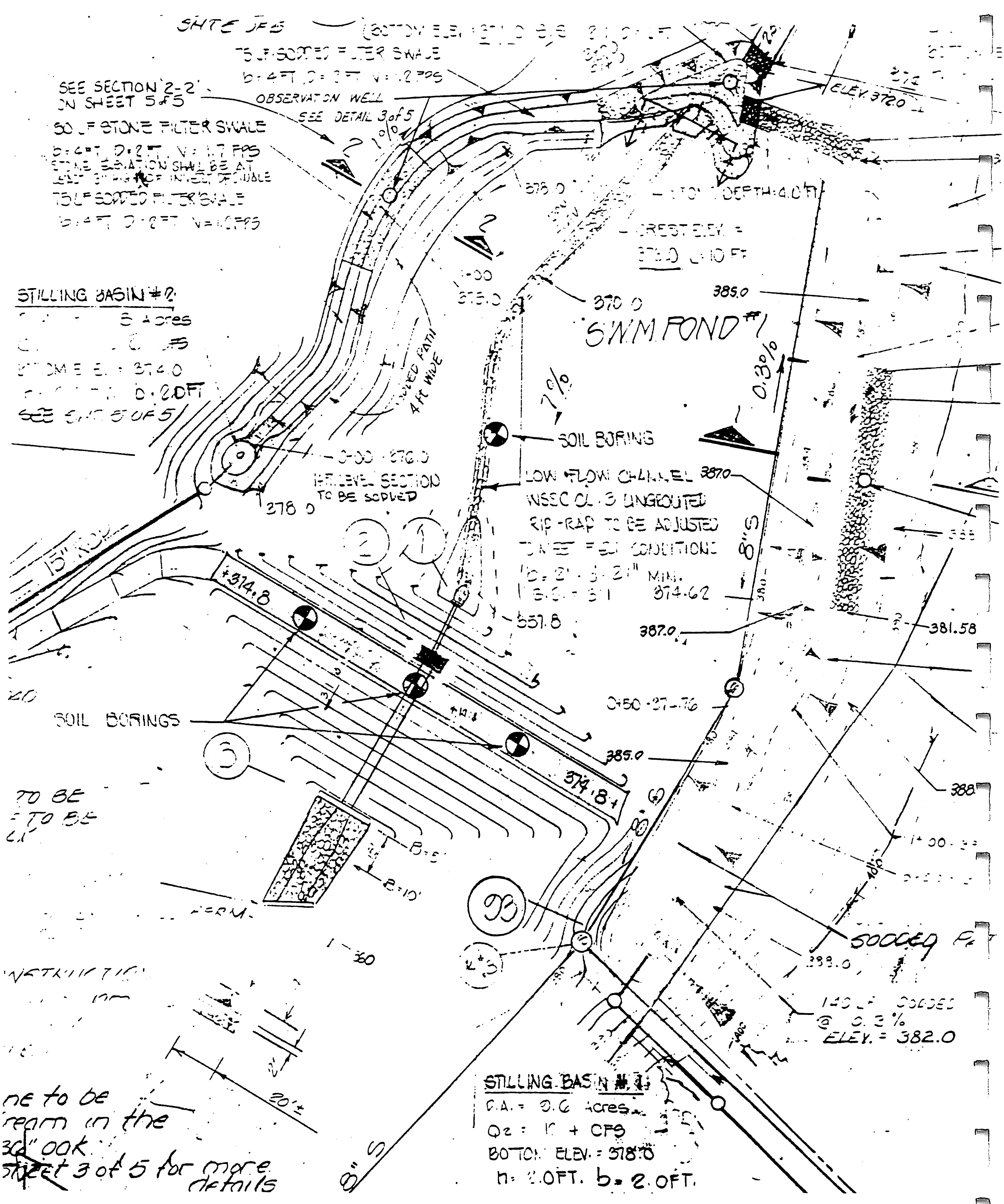
View of terraced side slopes and large, dry storage pool area.



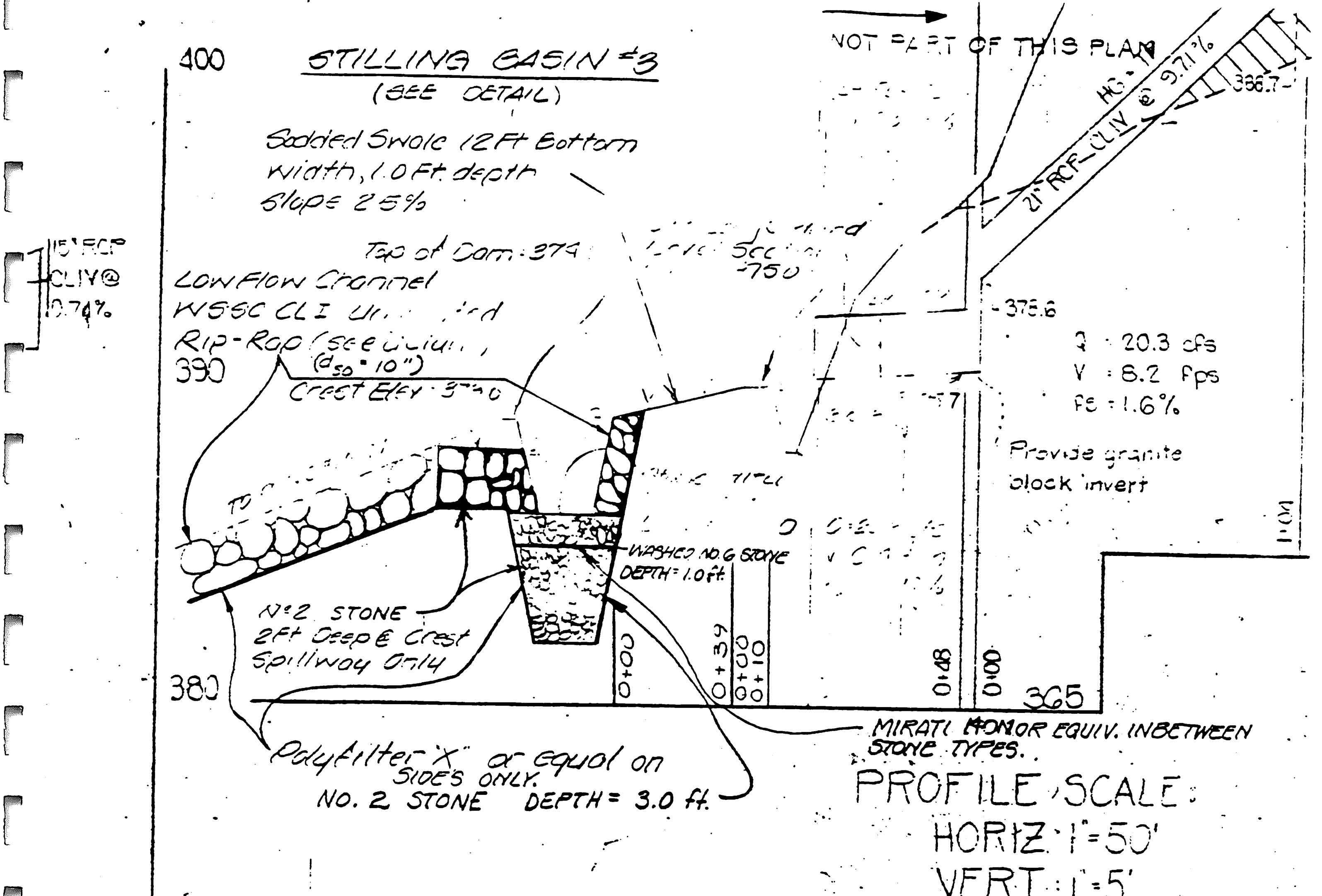
Pre-treatment of runoff via system of stilling basins and grass swales.

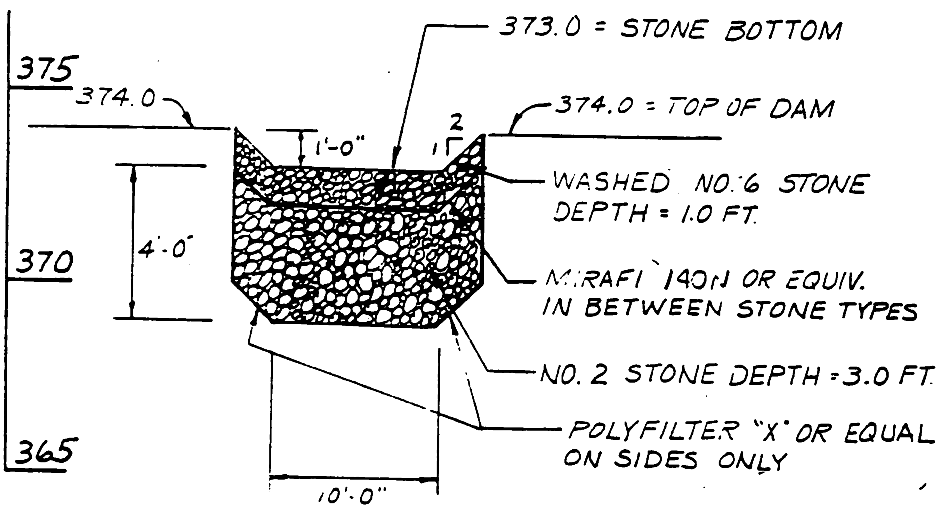
Grass swale

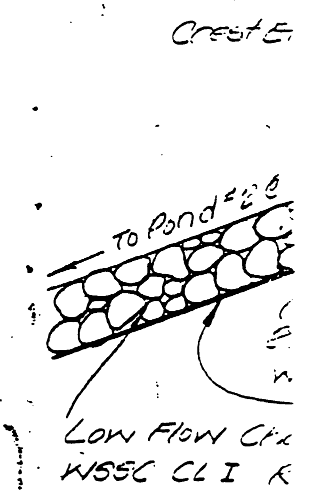
Infiltration trench (one of 3) sized to treat 0.25" of street runoff.



FAIRLAND RIDGE







SECTION 4-4

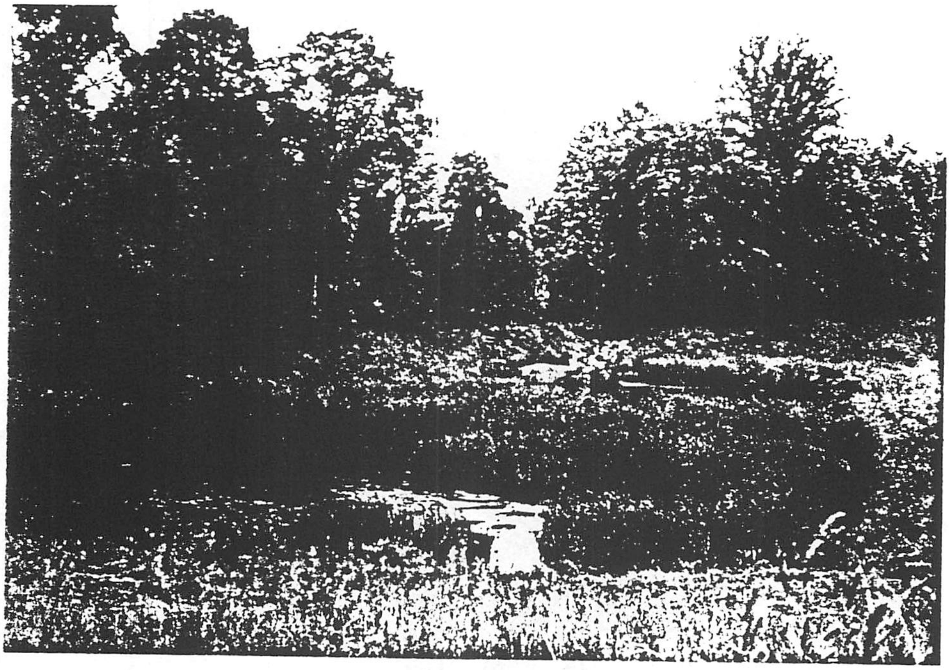
SCALE: HORIZ. 1" = 20'
VERT. 1" = 5'

FAIRLAND RIDGE

JOHNSON

Appendix A: BMP Monitoring Sites

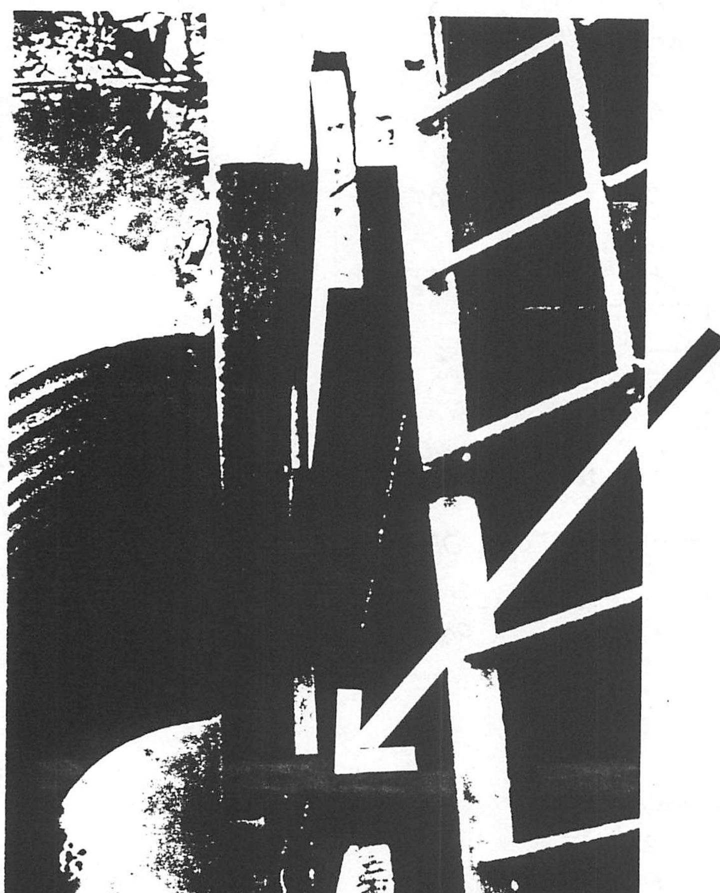
2. Oaksprings ED Artificial Wetland



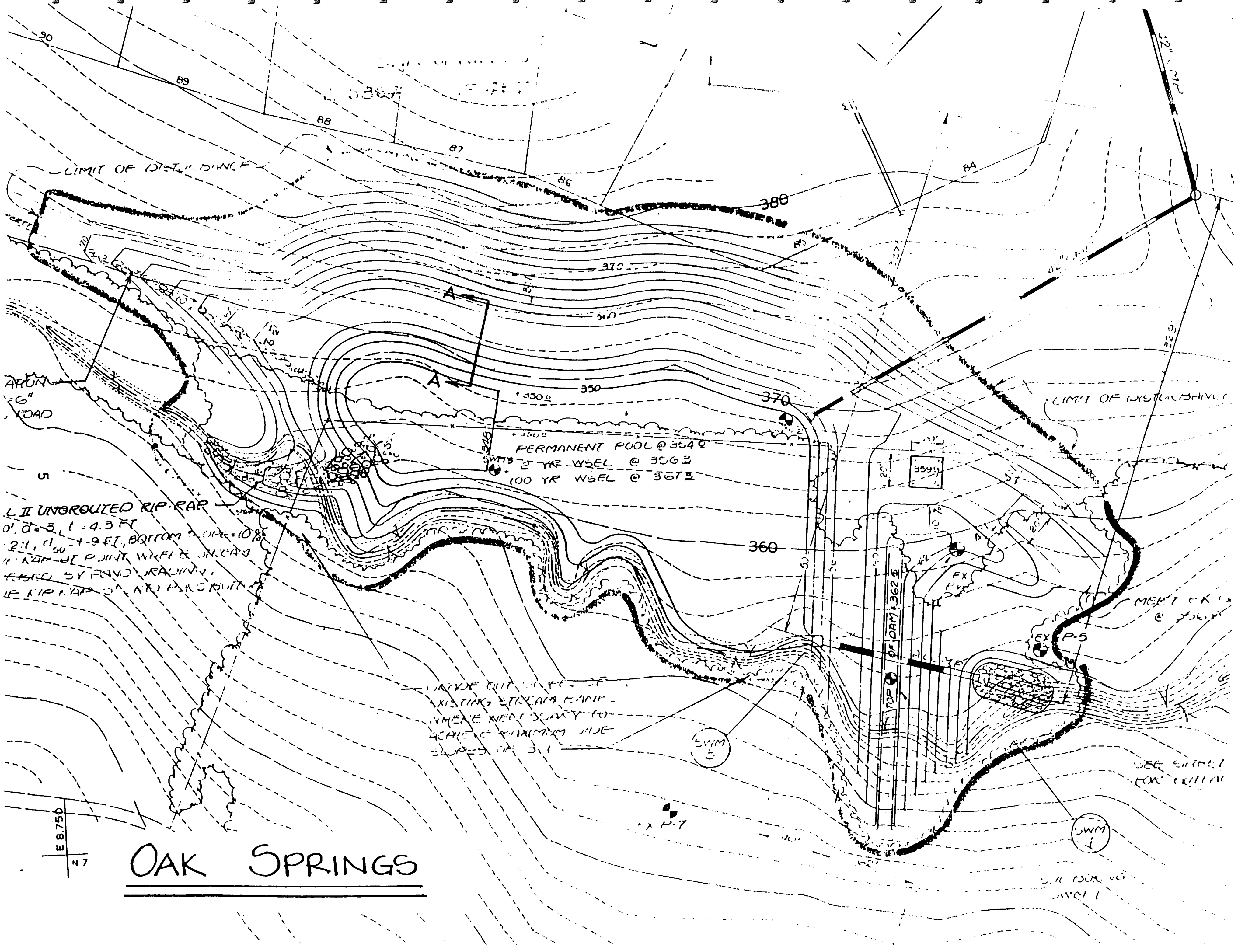
Background/ Features

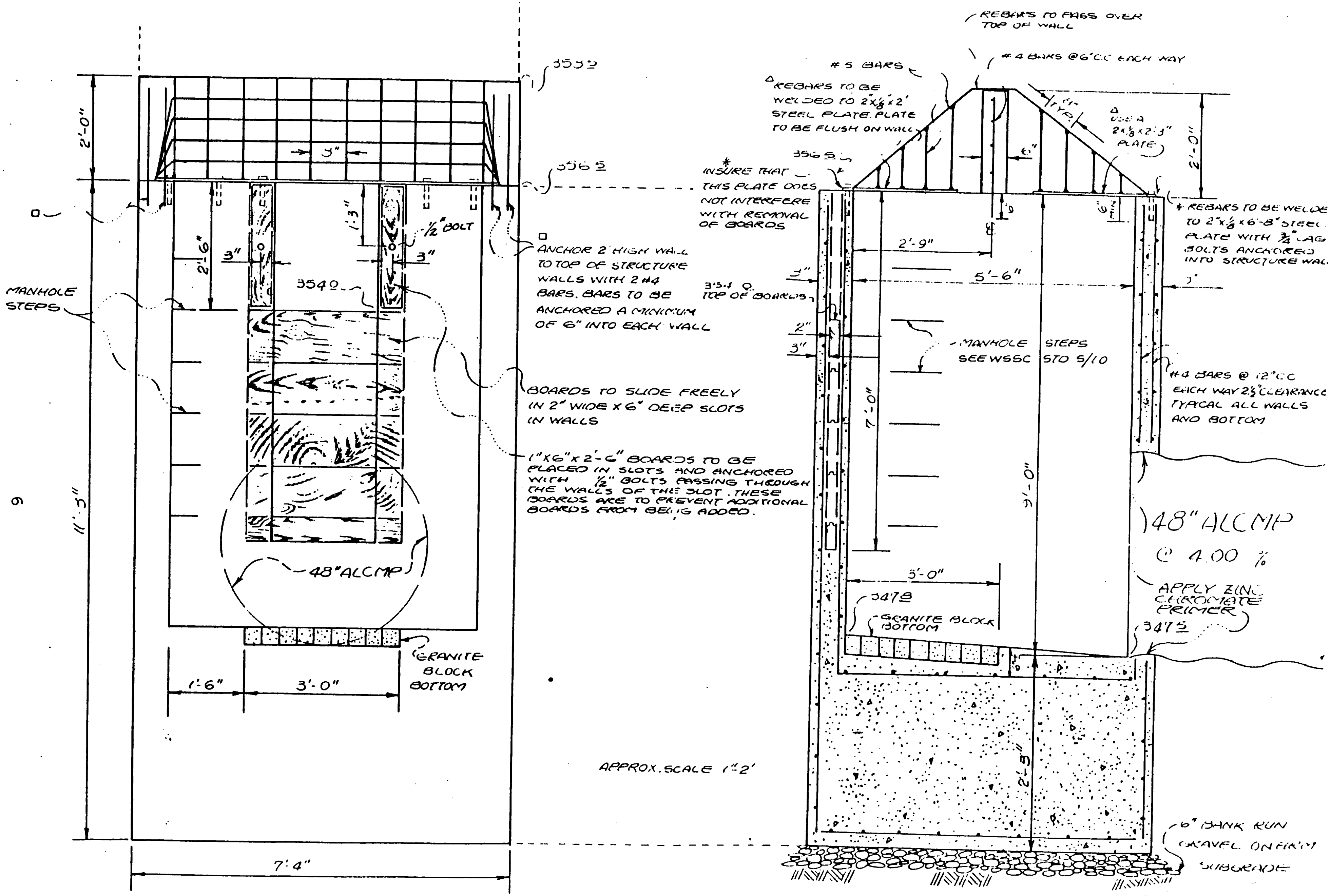
- DA to BMP: 140.0 ac.
- Imperviousness: 18%
- Full 2-year water quantit[illegible] control
- ED water quality control

Cattails and other emergent aquatic vegetation cover approximately 50% of this 1.0 acre wetland.



View of notched, wooden flashboard system for ED water quality control.


LIMIT OF DISTURBANCE
380
370
360
350
A
A
PERMANENT POOL @ 354.0
2 YR WSEL @ 356.3
100 YR WSEL @ 367.2
TOP OF DAM 362.5
EX P-5
P-7
SWM 1
SWM 3
II UNGROUTED RIP-RAP
OAK SPRINGS
E 8,750
N 7
5



FRONT VIEW

SIDE VIEW

DETAIL #3

OAK SPRINGS

Appendix A: BMP Monitoring Sites

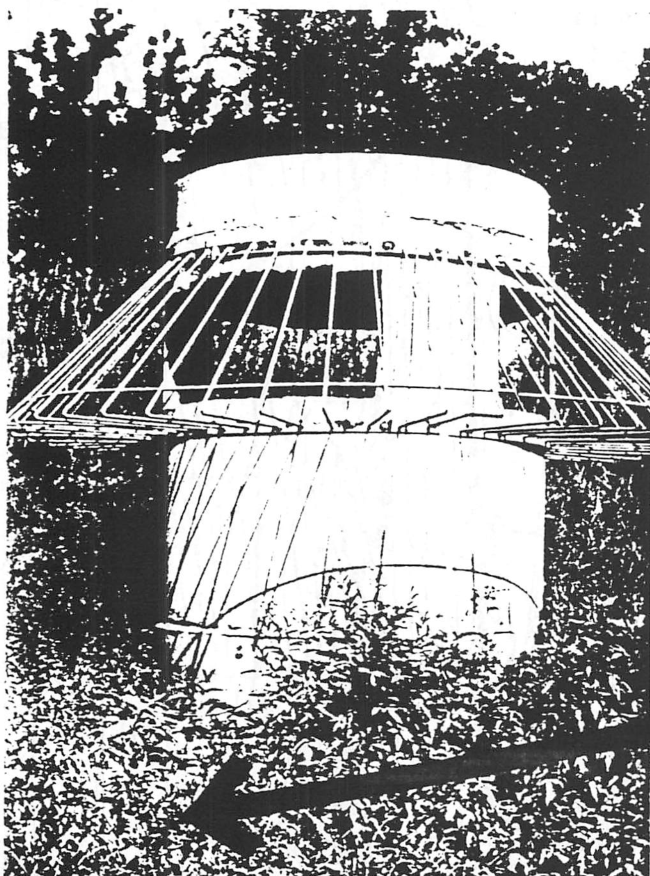
3. Tanglewood ED Dry Pond

Background/ Features

- DA to BMP: 195.0 ac.
- Imperviousness: 30%
- Full 2-year water quantity control
- ED water quality control

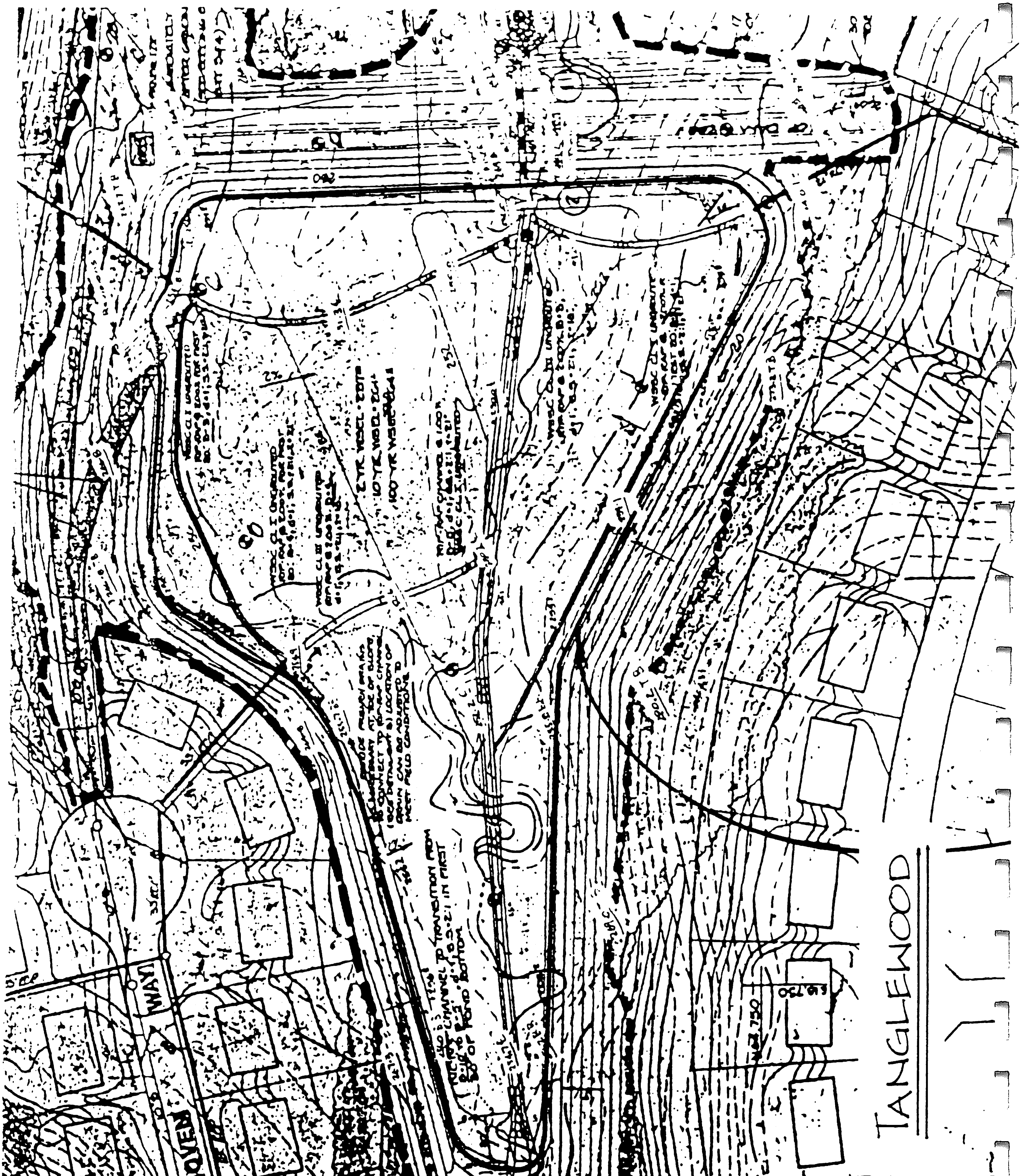
Earthen dam

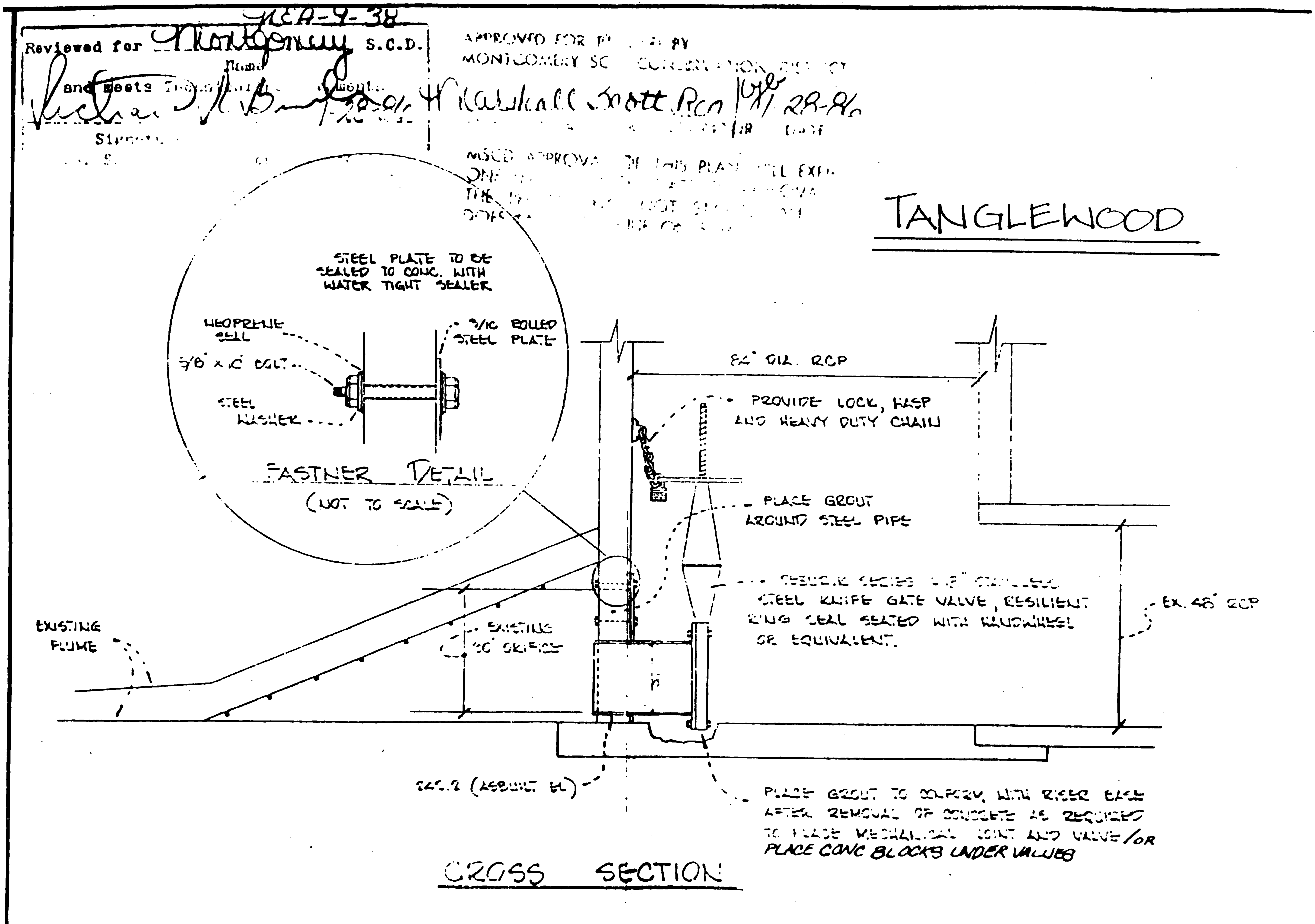
View of large,dry storage pool with partially shaded 500 ft. long pilot channel.



Low flow pipe features adjustable 18" gate valve for ED water quality control.

Low flow offfice


TANGLEWOOD
WAY


KEA-9-38
Reviewed for Montgomery S.C.D.
and meets
APPROVED FOR
MONTGOMERY SO
TANGLEWOOD
STEEL PLATE TO BE SEALED TO CONC. WITH WATER TIGHT SEALER
NEOPRENE SEAL
5/8" x 10" BOLT
STEEL WASHER
3/16 ROLLED STEEL PLATE
FASTNER DETAIL
(NOT TO SCALE)
84" DIA. RCP
PROVIDE LOCK, HASP AND HEAVY DUTY CHAIN
PLACE GROUT AROUND STEEL PIPE
STEEL KNIFE GATE VALVE, RESILIENT RING SEAL SEATED WITH HANDWHEEL OR EQUIVALENT.
EX. 48" RCP
EXISTING FLUME
EXISTING 30" ORIFICE
(ASBUILT EL)
PLACE CONC BLOCKS UNDER VALVES
CROSS SECTION

Appendix A: BMP Monitoring Sites

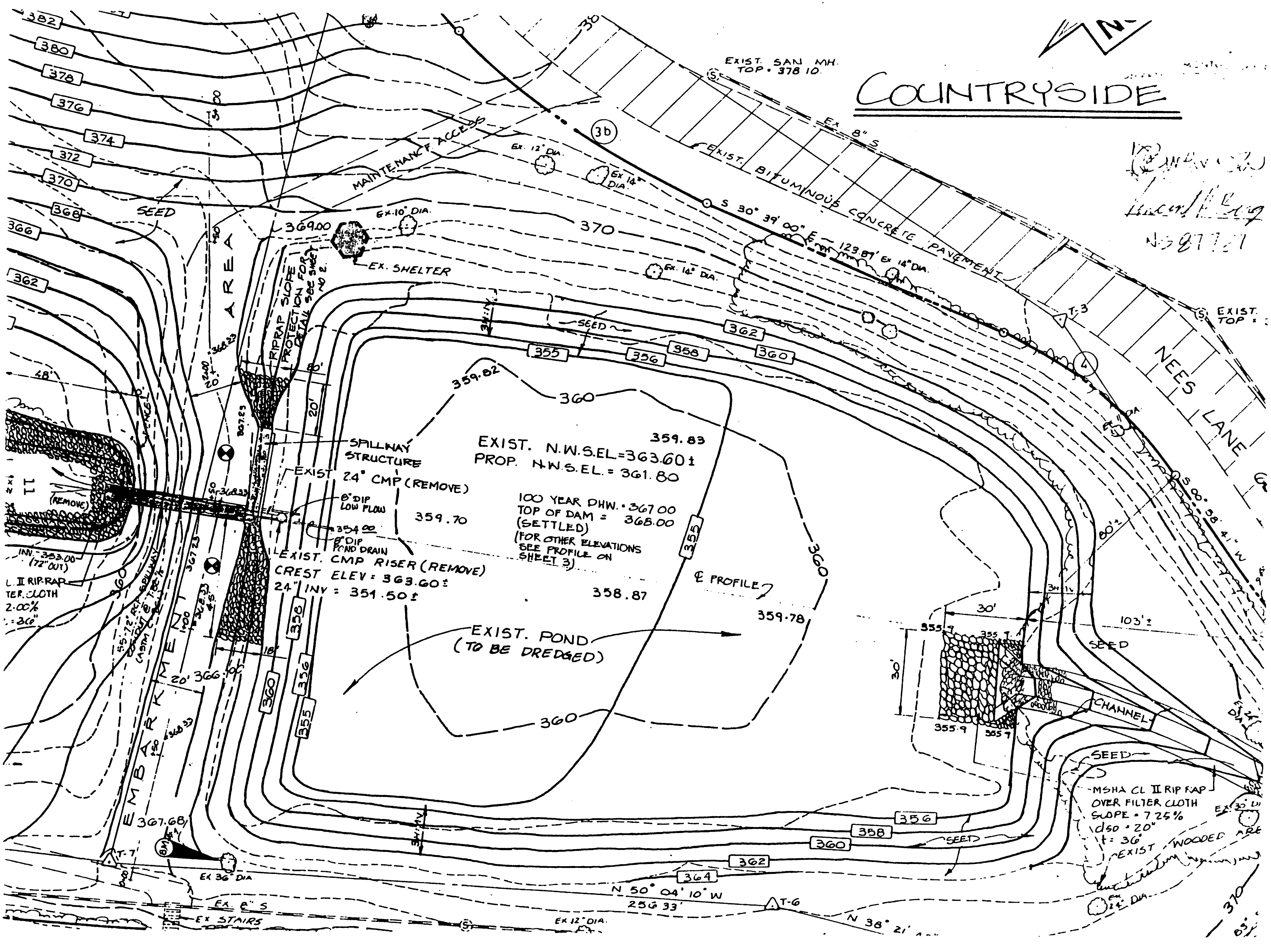
4. Countryside Wet Pond

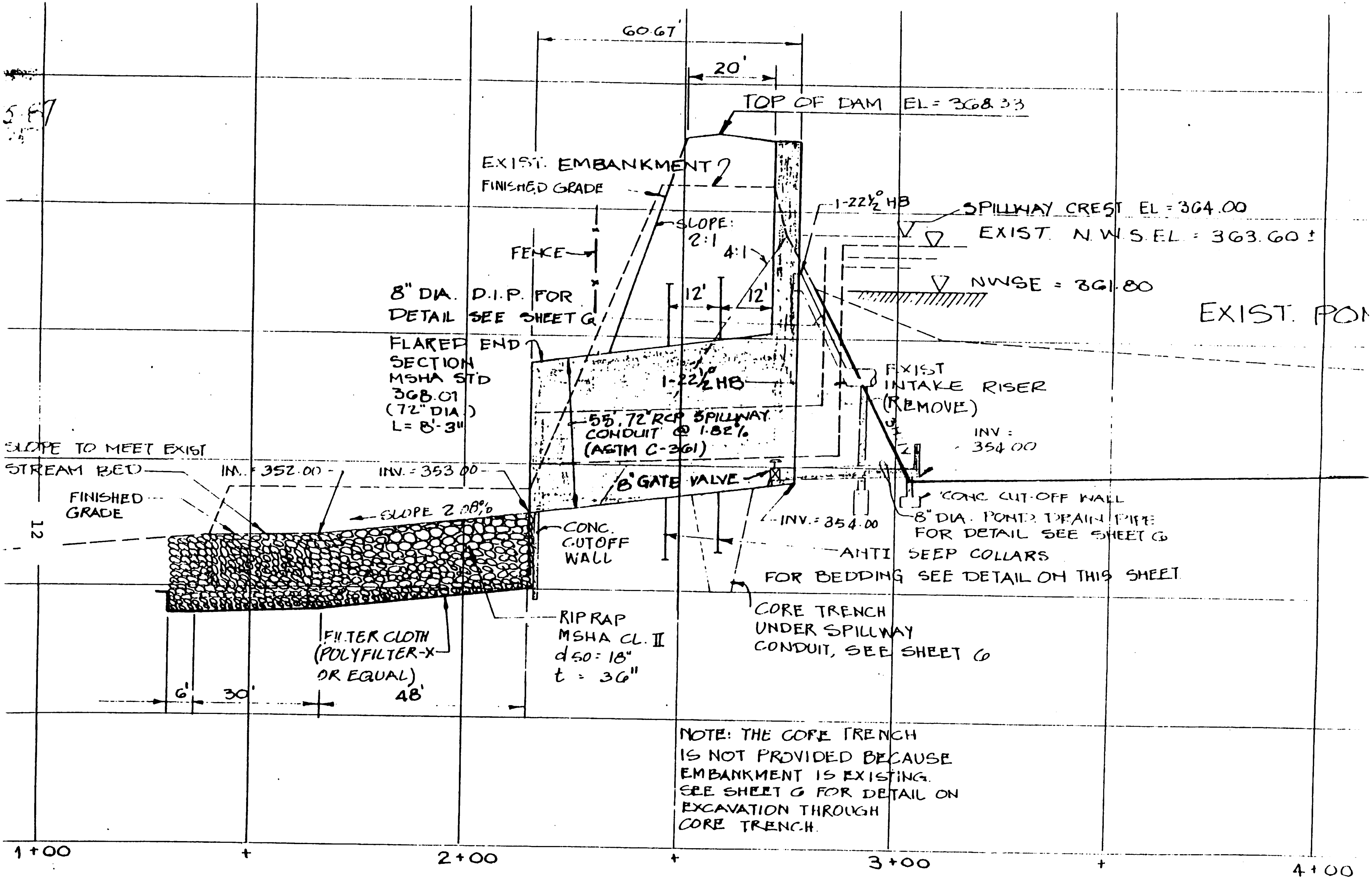
1.5 surface acre wet pond with emergent fringe marsh.

Background/ Features

- DA to BMP: 165.0 ac.
- Imperviousness: 12%
- Full 2-year water quantity control
- Incidental water quality control
- Reverse sloping outlet pipe

View of 72"RCP barrel and 30 ft. wide rip-rap outfall area.

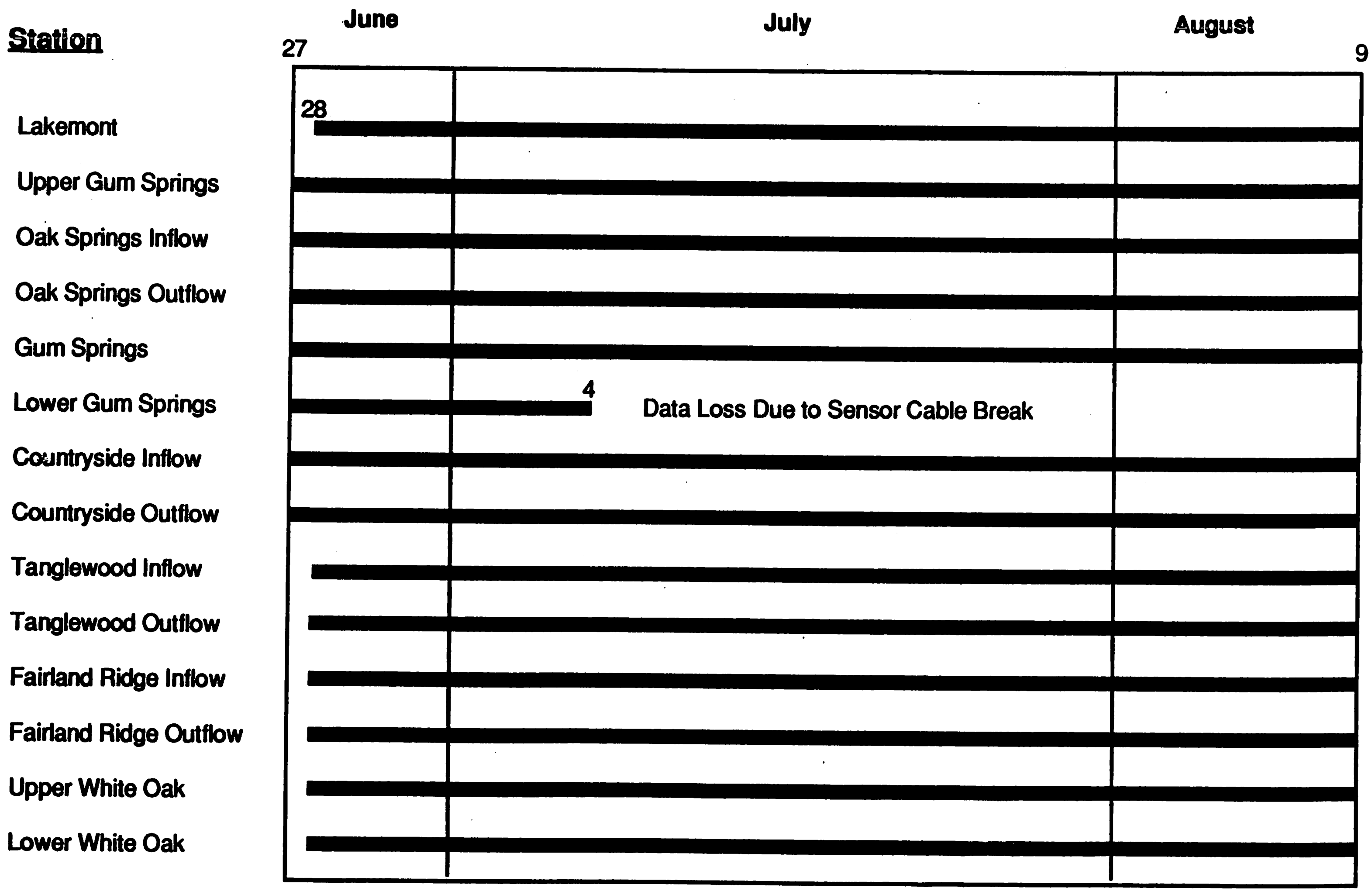

COUNTRYSIDE
EXIST. SAN. MH. TOP • 378.10
EX. 8" S
EXIST. BITUMINOUS CONCRETE PAVEMENT
S 30° 39' 00" E 123.87'
NEES LANE
EXIST. TOP
MAINTENANCE ACCESS
AREA
EX. SHELTER
RIPRAP SLOPE PROTECTION FOR DETAIL SEE SHEET NO 2
SPILLWAY STRUCTURE
EXIST 24" CMP (REMOVE)
8" DIP LOW FLOW
8" DIP POND DRAIN
EXIST. CMP RISER (REMOVE)
CREST ELEV = 363.60±
24" INV = 351.50±
EXIST. N.W.S.EL.=363.60±
PROP. N.W.S.EL. = 361.80
100 YEAR DHW. = 367.00
TOP OF DAM = 368.00
(SETTLED)
(FOR OTHER ELEVATIONS SEE PROFILE ON SHEET 3)
EXIST. POND
(TO BE DREDGED)
℄ PROFILE
CHANNEL
SEED
MSHA CL II RIP RAP OVER FILTER CLOTH
SLOPE = 7.25%
d50 = 20"
t = 36"
EXIST. WOODED AREA
EMBANKMENT
EX STAIRS
N 50° 04' 10" W
256.33'
N 38° 21'
(REMOVE)
INV. = 353.00 (72" OUT)
359.82
359.83
359.70
358.87
359.78
369.00
367.68
11



COUNTRYSIDE

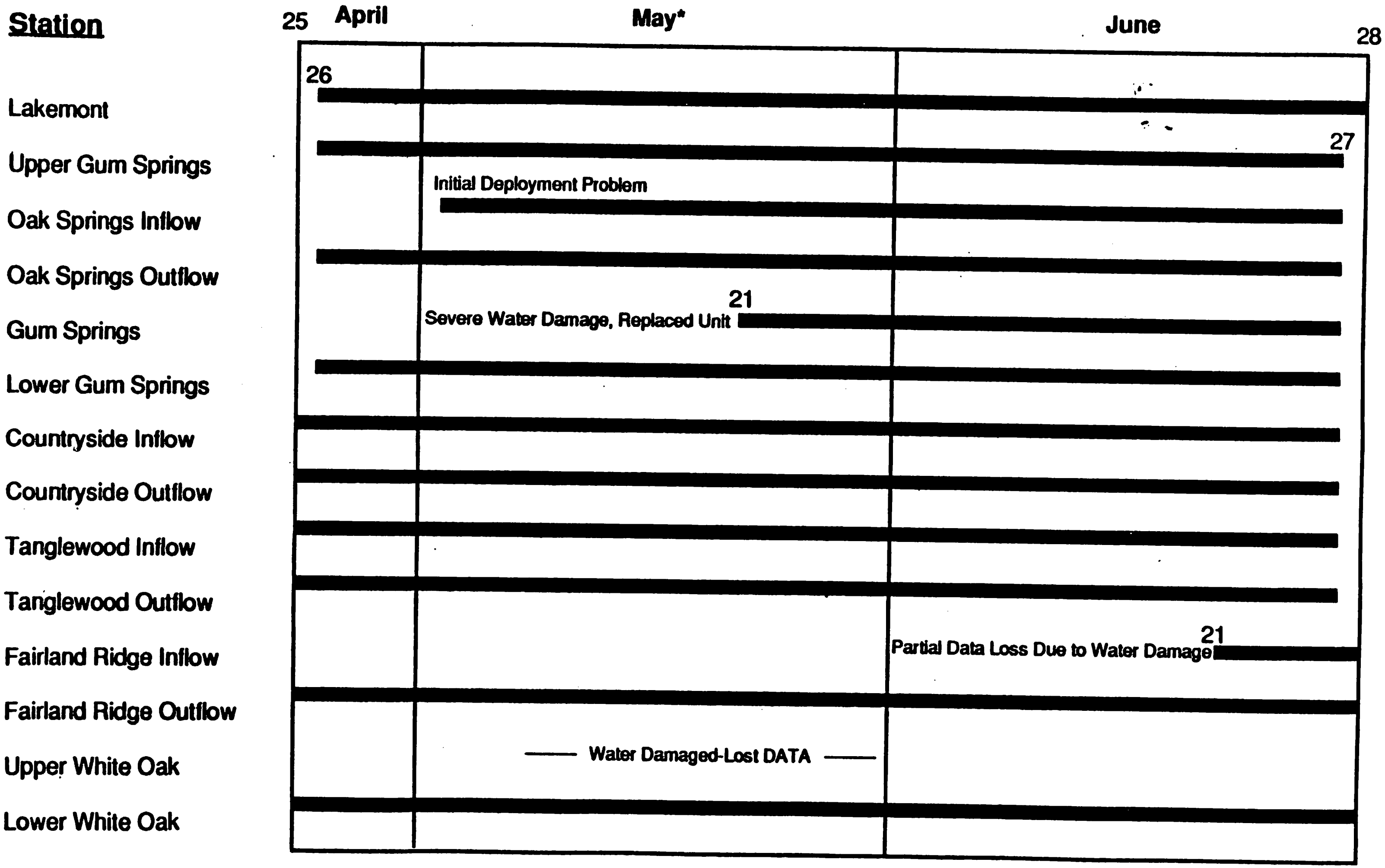
PROFILE ALONG ℄ OF SPILLWAY

SECOND DEPLOYMENT PERIOD



Appendix B

FIRST DEPLOYMENT PERIOD



* 10-year frequency storm event, May 6-7.

THIRD DEPLOYMENT PERIOD