Rick Mystrom, Mayor

Anchorage Climate Characteristics for Use in Storm Water Management

Document No. WMP APr99004

MUNICIPALITY OF ANCHORAGE
WATERSHED MANAGEMENT PROGRAM

DECEMBER 1999

WATERSHED
MANAGEMENT

Department of
Public Works

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WATERSHED MANAGEMENT

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Abbreviations

AIA	Anchorage International Airport
CSO	combined sewer overflows
DPW	Department of Public Works
EPA	U.S. Environmental Protection Agency's
MOA	Municipality of Anchorage
NCDC	National Climatic Data Center
NPDES	National Pollution Discharge Elimination System
NWS	National Weather Service
SSO	sanitary sewer overflows
SWMM	Storm Water Management Model
SYNOP	synoptic rainfall data analysis program

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Introduction

This report provides information about Anchorage's unique climate characteristics that influence and affect storm water management within the Municipality of Anchorage (MOA). The first section, Climate Characteristics, focuses on aspects of Anchorage weather, including precipitation and temperature, which relate to stormwater runoff and management. The second section, Anchorage Hydrology, focuses on local hydrology relating to storm system discharges.

Purpose

Discharges from MOA's storm drainage system are covered by the U.S. Environmental Protection Agency's (EPA) National Pollution Discharge Elimination System (NPDES) storm water discharge permit for municipal separate sewer systems. Under this permit, storm water is defined as "storm water runoff, snowmelt runoff and surface runoff and drainage" (40 CFR 122.26(b)). A major emphasis in the NPDES storm water program is development of municipal programs for the identification and monitoring of illicit connections and illegal dumping to storm water drainage systems. These discharges are not considered storm water discharges and are not covered by the NPDES storm water discharge permit. The NPDES regulations require completion of dry weather screening of selected municipal outfalls or other field-screening points for non-storm water discharges. Thus, a determination of dry weather, and its counterpart, wet weather, is required to properly time the season for these screenings.

Scope

The scope of this report is to characterize elements of the Anchorage climate that directly or indirectly lead to storm water discharges. Rainfall and snowfall volumes and seasons, snowmelt seasons, and storm event volumes and durations are reviewed and discussed. Hydrological conditions affecting runoff are also described.

Background

NPDES permitting distinguishes wet weather periods from dry weather periods. Wet weather periods include discharges from storm water sewer systems attributable to precipitation; dry-weather periods include flows attributable to groundwater infiltration, illicit discharges, or other non-precipitation sources.

Storm water and wastewater regulations promulgated by the EPA do not contain a definition of dry or wet weather, wet weather events, dry or wet weather flows, or wet weather periods (Brennan, et al., 1999). However, these terms are used in guidance documents (Table 1). According to EPA's Office of Wastewater Management "Frequently Asked Questions" (www.epa.gov/owmitnet), urban wet weather discharges result from precipitation events, such as rainfall or snowmelt, combined sewer overflows (CSOs), and sanitary sewer overflows (SSOs).

Table 1
EPA DOCUMENTS REFERENCING WET WEATHER FLOW

Title	Source	Date
Update to Training Manual for NPDES Permit Writers	EPA	1993
Wet Weather Flow Research Plan	EPA	1996
40 CFR 122.26 (b)(13) and (d)(1)(iv)(D) Storm Water Discharges	Code of Federal Regulations	
Guidance Manual for the Preparation of Part 1 of the NPDES Permit Applications for Discharges from Municipal Separate Storm Sewer Systems	EPA Office of Water EPA-505/8-91-003A	April 1991
Guidance Manual for the Preparation of Part 2 of the NPDES Permit Applications for Discharges from Municipal Separate Storm Sewer Systems	EPA Office of Water EPA-833/B-92-002	November 1992
Combined Sewer Overflow Control Policy	EPA Office of Water EPA 830-B-94-001	April 1994
Interim Permitting Approach for Water Quality-Based Effluent Limitations in Storm Water Permits	EPA	August 1996
Developing Watershed –Based Monitoring Strategies for the Management of Wet Weather Flows	Urban Wet Weather Flows Federal Advisory Committee Watershed Work Group	February 6, 1997
A Watershed Alternative for the Management of Wet Weather flows or A Watershed Alternative for the Achievement of Water Quality Objectives – DRAFT –	Four versions (Caucus representative, Environment and Health Caucus comments, Municipal Caucus comments, and EPA comments).	November 1997
Stormwater Phase II Proposed Rule	Federal Register	January 9, 1998

The MOA's storm water discharge permit covers discharges from Anchorage's storm drainage system. SSOs occur in sanitary sewer systems and would not be discharged from storm drainage systems. Since the Anchorage storm drainage system is not combined with the sanitary sewer system and CSOs would not result from wet weather, at Anchorage, wet weather flows solely are the result of precipitation.

Anchorage storm drainage systems do carry measurable amounts of infiltration due to the high groundwater table found in portions of the municipality, as documented in the field work for the Part 1 permit application (MOA, 1992a). Thus, discharges from the storm drainage systems do not consist entirely of surface precipitation runoff. The definition of wet and dry weather periods is necessary to differentiate between these base flow discharges and discharges associated with precipitation. Consequently, the definition of wet weather periods will be keyed to precipitation, which, as mentioned above, includes rainfall and snowmelt.

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Anchorage Climate Characteristics

Climate data presented in the following sections are based on records maintained at a station at Anchorage International Airport (AIA) by the National Weather Service (NWS).

Annual and Monthly Amounts of Precipitation

Anchorage receives an average of 15.7 inches of precipitation annually; 10.7 inches fall as rain and 5.0 inches of water-equivalent fall as snow. Daily data for precipitation, rainfall, snowfall, maximum and minimum temperatures, and snow on the ground for the period of November 1953 through July 1998 are summarized. Hourly precipitation from the same site was available for 1963 through 1988. Monthly and annual statistics are shown in Table 2.

Table 2
ANNUAL ANCHORAGE TEMPERATURES AND PRECIPITATION

MONTH	MEAN TEMPERATURE (DEGREES F)	MEAN PRECIPITATION (INCHES)	PRECIPITATION AS RAIN (INCHES)	PRECIPITATION AS SNOW (INCHES)	MEAN SNOWFALL (INCHES)
January	14.7	0.76	0.13	0.63	9.2
February	18.4	0.85	0.07	0.77	12.8
March	25	0.62	0.11	0.50	9.4
April	36	0.59	0.22	0.37	5.1
May	46.9	0.64	0.61	0.03	0.2
June	54.8	1.00	1.00	0.00	0
July	58.4	1.84	1.84	0.00	0
August	56.3	2.65	2.65	0.00	0
September	48.2	2.68	2.62	0.05	0.2
October	34.2	1.84	1.07	0.77	8.1
November	21.5	1.13	0.29	0.84	12.0
December	15.9	1.08	0.12	0.96	14.2
Annual	35.9	15.67	10.73	4.94	71.2

Source: Alaska State Climatologist for Anchorage International Airport

STORM ANALYSIS ON ANNUAL BASIS

Individual rainfall events were identified using historic hourly precipitation data and the EPA's synoptic rainfall data analysis program (SYNOP). These data were obtained in National Climatic Data Center (NCDC) format, as written to compact disk by EarthInfo, Inc. (EarthInfo, 1994). Months used in the analysis are shown in Table 3, as reported by the SYNOP program. Note that more than 40 months had only a single meter reading. These data appear to be erroneous and were not used in the storm event analysis. In addition, several months and years lacked data, as denoted by asterisks, and likewise were not used in the analysis. 247 complete months of data were used in the analysis, spanning 26 years, 1963 through 1988. Three complete years are missing, as are several months of other years in the period. Only 16 years had a complete record for all twelve months.

Table 3
NUMBER OF HOURLY PRECIPITATION READINGS PER MONTH

Year	No. of months	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
63	12	69	53	75	84	8	65	57	76	32	42	10	40
64	12	16	55	57	37	29	62	32	75	34	71	57	38
65	12	20	27	30	20	19	30	51	49	157	58	66	59
66	12	20	36	25	34	37	10	21	73	64	26	57	44
67	12	50	49	58	22	29	72	78	74	89	22	53	80
68	12	31	105	20	34	43	12	43	22	38	55	42	28
69	12	18	38	4	1	14	8	48	14	20	29	28	32
70	12	37	32	16	18	13	27	61	75	41	68	43	49
71	4	11	65	41	30	****	****	****	****	****	****	****	****
72	4	****	****	****	1	1	1	1	1	105	76	25	33
73	12	40	5	42	14	4	31	22	67	17	54	34	20
74	12	2	66	27	29	12	20	32	54	37	76	37	103
75	12	28	47	41	73	13	20	34	27	90	27	8	45
76	12	54	12	79	35	7	11	18	37	89	46	77	52
77	12	35	17	37	70	12	21	25	42	87	71	28	29
78	12	23	57	23	2	2	68	62	14	60	72	40	61
79	12	14	21	4	37	7	41	85	48	97	77	93	57
80	12	63	25	21	10	45	75	76	80	88	91	17	13
81	11	30	46	20	13	29	21	112	118	41	113	50	****
82	9	****	27	21	15	19	45	60	64	88	69	****	****
83	6	****	1	1	55	21	20	17	57	20	****	****	1
84	8	11	56	5	11	18	34	39	58	1	1	1	1
85	0	1	1	1	1	1	1	1	1	1	1	1	1
86	0	1	1	1	1	1	1	1	1	1	1	1	1
87	5	1	1	1	1	1	1	1	9	50	59	66	56
88	8	12	14	30	21	15	1	22	68	36	1	1	1
No. of months	247	20	21	21	22	21	20	21	22	22	20	19	18

****	No readings available.
▨	Indicates monthly for which readings were not used in analysis.

The following criteria were assigned to allow SYNOP to determine a discrete storm event:

- Two types of storm event volumes were specified. For one type, the precipitation volume was not limited; that is, any rainfall greater than zero was included in the analysis. The other type of event required a minimum volume of 0.1 inches.
- January 1 through December 31 was the timeframe used for precipitation.
- An inter-event time was determined, based on the lowest inter-event time that produced a series of time-between-storms (“deltas”), whose coefficient of variation was

approximately 1, as recommended in the SYNOP documentation. Delta is the length of time between the midpoints of consecutive storms. Inter-event time is the minimum number of hours without precipitation between storms. This inter-event time was determined by executing the program with varying specified inter-event times and examining the coefficients of variation of the values calculated for "delta" until an optimal value (close to 1) was found. For both storm event volumes, the coefficient of variation hovered around 1 for various specified inter-event times. The lowest inter-event time for which the coefficient of variation was approximately 1 was used. For storms with no minimum volume, an inter-event time of 16 hours was determined. For storms with a minimum volume of 0.10 inch, an inter-event time of 30 hours was determined.

For volumes greater than 0.0 inches, SYNOP found 1,564 total storms for the 247 months of analysis. These storms averaged 14 hours in duration and 0.20 inches in volume, as shown in Table 4. For storm volumes equal to or greater than 0.1 inches, SYNOP identified 669 storms. These storms averaged 40 hours in duration and 0.44 inches in volume.

Table 4
PRECIPITATION STATISTICS BY STORM

Storm	Number of events	Total	Minimum	Maximum	Average	Coefficient of variation
Storm Volume > 0.0 in						
Duration (hours)	1564	22043	1	132	14.09	1.12
Intensity (inches per hour)	1564	24.7659	0.0012	0.12	0.0158	0.83
Volume (inches)	1564	313.53	0.01	3.1	0.2	1.37
Delta[1] (hours)	1551	178262	17.5	920	114.93	1
Storm Volume => 0.1 in						
Duration (hours)	669	26504	2	246	39.62	0.83
Intensity (inches per hour)	669	10.2637	0.0014	0.075	0.0153	0.83
Volume (inches)	669	292.64	0.1	3.46	0.44	0.92
Delta[1] (hours)	658	182757.5	38	2188	277.75	1

[1] Delta is the length of time between midpoints of consecutive storms. The period between the last storm of one year and first storm of the next year is not included.

Annual statistics were also derived and are shown in Table 5. Data were not complete for all years; only years with 12 complete months were used in this summary. For all storm events with volumes greater than 0.0 inches, there was an average of 76 storms per year with a mean total annual duration of 1055 hours and a mean annual volume of 14.6 inches. For all storm events with volumes greater than 0.1 inches, there was an average of 32 storms per year, with a mean total annual duration of 1258 hours and a mean annual volume of 13.6 inches.

Table 5
ANNUAL STORM EVENT STATISTICS FOR YEARS WITH 12 MONTHS OF PRECIPITATION DATA

	Minimum	Maximum	Average
Storm Volume > 0.0 in			
Number of storms	58	93	76
Annual Volume (inches)	8.1	20.8	14.6
Annual Duration (hours)	566	1344	1055
Storm Volume => 0.1 in			
Number of Storms	23	40	32
Annual Volumes (inches)	7.4	20.3	13.6
Annual Duration (hours)	658	1776	1258

MONTHLY STORM EVENT STATISTICS

Monthly storm event statistics were also derived from the SYNOP analyses and are presented in Table 6 for two types of storms: all storms and only those storms with volumes greater than 0.1 inches. Averages were taken by month, based on the number of complete months of hourly precipitation. Storms with no minimum volume range in number from 4.8 to 8 per month. Those with a minimum volume of 0.1 inches range from 1.5 to 4.1 per month. July through October, the months with highest precipitation (Table 2), correspond to months with more storm events. Storms occurring in May through November have higher average intensities than storms occurring December through April.

Table 6
STORM EVENT STATISTICS BY MONTH

Minimum rainfall volume: 0.0 inches			Selected inter-event time: 16 hrs		
Month	**Average Duration Hours**	**Average Intensity inches/hour**	**Average Volume inches**	**Average Delta hours**	**Number of Storms avg/month**
January	12.9	0.014	0.16	141	4.9
February	14.1	0.013	0.15	113	5.9
March	11.8	0.012	0.11	143	5.6
April	13.1	0.014	0.14	138	4.8
May	8.1	0.015	0.12	161	5.0
June	14.1	0.016	0.20	126	5.6
July	13.7	0.018	0.22	103	7.8
August	17.7	0.019	0.28	91	7.5
September	17.6	0.018	0.28	91	8.0
October	15.8	0.018	0.26	95	7.7
November	12.6	0.016	0.20	102	6.4
December	13.3	0.014	0.17	120	6.7

Minimum rainfall volume:	0.1 inches		Selected inter-event time:	30 hrs	
Month	**Average Duration Hours**	**Average Intensity inches/hour**	**Average Volume inches**	**Average Delta hours**	**Number of Storms avg/month**
January	34.2	0.014	0.34	410	2.3
February	42.9	0.011	0.33	303	2.4
March	41.1	0.010	0.31	340	1.7
April	36.8	0.014	0.31	391	1.9
May	23.3	0.020	0.26	543	1.5
June	32.8	0.015	0.43	321	2.6
July	42.3	0.017	0.52	264	3.0
August	41.0	0.017	0.52	204	4.0
September	46.0	0.017	0.54	183	4.1
October	40.9	0.017	0.52	187	3.6
November	36.6	0.017	0.42	223	2.8
December	44.0	0.011	0.40	295	2.6

Notes:
Source: SYNOP program
Beginning year: 1963
Ending year: 1988
Delta is the number of hours from the midpoint of one storm to the midpoint of the next.
Inter-event time is the minimum number of hours without precipitation between storms

Snowfall and Snowmelt

ANNUAL SNOWFALL, SNOWFALL SEASON, AND SNOW ON THE GROUND

Anchorage receives snowfall 7 months of the year, averaging 71 inches of snowfall annually. Snowfall has been recorded as early as September 22 (1996) and as late as May 26 (1983). Heaviest snowfall in Anchorage occurs in February and March (Table 1).

Snow remains on the ground from October through the middle to end of April (Figure 1) in maximum annual depths of recorded snow on the ground ranging from 8 to 47 inches; the average annual maximum is 20 inches on the ground. The average first day of snow on the ground that remains for at least 3 days is October 22. The average last day of snow on the ground is April 10. Data reflect snow on the ground in undisturbed areas, typical of yards and landscaped areas; streets and parking lots are generally cleared of snow. A thin layer of snow may remain over the winter in these areas, or they may become entirely snowfree, depending on the amount of traffic. Finally, snow may be concentrated in snow storage sites, often adjacent to roadways and parking lots.

SEASONAL TEMPERATURES

Daily temperatures average below 32° F from October 18 through April 1 (165 days or 45 percent of a year). On an annual basis, the average daily temperature rises above 32° F for

28 days during this period; the minimum temperature rises above 32° F for 3 days. For the months of November through February, the daily temperature averages above 32° F an average of 14 days a year; the minimum temperature rises above 32° F on only 2 days a year.

SNOWMELT MECHANICS

Snowmelt involves heat input to the snowpack. The surface of the snowpack, exposed to sunlight and the ambient air temperature, thaws first. Melted snow migrates down into the pack until it refreezes. As it migrates through, melted snow transfers heat, warming lower layers of the pack. Eventually, enough of the snowpack is warmed to allow melted water to flow out of the snowpack and actual discharge of snowmelt occurs. Thinner layers of snow (e.g., snow and ice on paved surfaces) require less heat input and therefore, less time is required to initiate snowmelt. Since these areas are generally hydraulically connected to the storm drainage system, snowmelt discharge occurs rapidly compared to snowmelt discharge from undisturbed snow or snow at storage sites.

The duration of the melt season is affected by:

- Heat input, measured by melting degree-hours (the number of degree-hours per day above 32° F).
- Amount of solar insolation (direct sunlight).
- Amount of wind.
- Precipitation on the snowpack (rain will accelerate the melt; snow will tend to decelerate it).

Of these, heat input is the most easily measured and is generally assumed to have the greatest effect.

MIDWINTER THAWS

Short periods of thaw, in the form of rising temperatures, occasionally accompanied by rain, can occur during the winter months (November through February). Short periods of rain on snow occur about seven days each winter, with an average annual volume of 0.7 inches. Discharges from these precipitation events generally do not occur, since rainfall is absorbed by the snowpack, unless significantly warm temperatures accompany the rainfall. Runoff from these events is minimal because:

- The events are of short (2-3 days) duration.
- Direct solar insolation is limited, due to short daylight hours (especially November through February).

- The snowpack absorbs melted water and rainfall.
- Liquid water is refrozen lower in the snowpack, where the temperature remains at or below 32° F.

When rainfall is heavy and the temperatures are sufficiently warm, rainfall on streets and snowless areas runs off and floods drainage structures, which may be frozen. In these instances, standing water occurs at catch basins and storm drain inlets.

SPRING BREAKUP

Two types of spring snowmelt can occur – the melt of snow held in snowpack, such as snow piles (from street cleaning) and yards; and the melt of ice and snow in thin layers on streets, parking lots, and sidewalks. Snow held in snowpack requires a longer period of time to melt.

MELT PERIODS BASED ON DEGREE-HOURS PER DAY ANALYSIS

Snowmelt, while influenced by many factors, is largely driven by melting degree-hours. An implicit assumption is that melting degree-hours correspond directly with amount of snowmelt and correspondingly, with snowmelt discharge.

Melting degree-hour days were calculated followed the methods used in the EPA Storm Water Management Model (SWMM) (EPA, 1992). SWMM creates hourly temperatures based on a sinusoidal interpolation between minimum and maximum daily values. The maximum temperature is assumed to occur 3 hours before sunset; the minimum at sunrise. A sinusoidal function can be fit to two points, the time and magnitude of the maximum and minimum temperature. From this function, hourly temperatures are derived. The positive difference between a given hourly temperature and 32° F is a degree-hour. The sum of all degree-hours for a given day is a degree-hour day.

Melting degree-hour days were calculated for the years 1955 through 1998, from January 1 until May 7. Daily degree-hours for each year created a series of degree-hour days. Two subseries were examined: the degree-hour days from January 1 until the last snow on the ground and the degree hour days between March 1 to April 15. The second subseries was based on the assumption that by April 15, snowmelt from areas adjacent to hydraulically connected impervious areas would have melted and that melted snow would infiltrate, rather than contribute to surface runoff. This approach was used to limit days with degree-hours (later in the melt period) that would skew the results.

To characterize snowmelt runoff, it was necessary to consider only days with sufficient degree-hours to initiate or continue snowmelt. However, degree-hour requirements may vary over the snowmelt season as the trend of warming temperatures is established and the snowpack ripens. For example, a day with 10 degree-hours, preceded by several days of warm temperatures, will result in more snowmelt runoff than a similar day not preceded by warm temperatures. The SWMM accounts for this, but the method is not easy to reproduce. For simplicity, four minimums of daily degree-hours were considered: 0, 5, 10, and 15 degree-hours per day. A minimum of 10 degree-hours in one day (e.g., 5 hours at 34°F; the other 19 hours below freezing) was assumed to be necessary to initiate snowmelt runoff when the threshold was set at 10 degree-hours per day. Four subseries for each of the two calendar periods discussed above were created. The first included all days with degree-hours greater than 0, the next considered all days with degree hours greater than 5 hours, and similarly for 10 and 15 degree-hours.

All daily degree-hour values greater than the minimum (0, 5, 10, and 15) of the resulting eight subseries were ranked and divided into four quartiles. The quartile breaks are shown in Table 7. Each value for a quartile break represents the melting degree-hours for the given day at 25, 50, 75 and 100 percent of the ranked sub-series. For instance, for the sub-series with degree-hours greater than 0 and for the season from January 1 to the last snowfall (column 2 in Table 7), there were 1,736 days with total melting degree-hours greater than 0. Twenty-five percent (quartile 1) of those days had 21 or less melting degree-hours in a 24-hour period; 50 percent (quartile 2) had 54 or less and 75 percent (quartile 3) had 106 or less. The maximum total melting degree-hours for given day for that sub-series (quartile 4) was 308.

The distribution of degree-hour days for the period January 1 to the day with no-snow-on-ground versus March 1 to April 15 were nearly identical. The choice of the beginning date is arbitrary; it does not appear to affect the distribution of degree-hour days. That is, the median of the four quartiles, whether including all of January through the end of snowmelt, or just those degree-hour days between March 1 and April 15, are nearly the same. However, the distribution when degree-hour days are evaluated based on a minimum degree-hour threshold does affect the distribution. The distribution of degree-hour days was fairly sensitive to this assumed minimum value.

Table 7
COMPARISON OF MELTING DEGREE-HOUR DAYS DISTRIBUTIONS

Threshold	**Degree-hrs >0**		**Degree-hrs >5**		**Degree-hrs >10**		**Degree-hrs >15**	
Season	Jan 1 last snow	Mar 1 - Apr 15	Jan-1 last snow	Mar 1 - Apr 15	Jan-1 last snow	Mar 1 - Apr 15	Jan-1 last snow	Mar 1 - Apr 15
Quartile	**Number of degree-hours per day at given quartile**							
1	21	23	27	29	34	36	40	41
2	54	55	58	58	65	63	72	69
3	106	103	111	109	117	116	121	119
4	308	273	308	273	308	273	308	273
Number of days with melting degree-hours above threshold								
Average	39	23	22	37	34	20	31	19
Total (44 yrs)	1736	1022	1614	957	1495	886	1385	829

The average and maximum annual series of melting degree-hour days is shown in Figure 2. This figure also shows the melting degree-hour days in 2 years, a relatively low year, and a relatively high year. Note the high degree of variability of actual degree-hour days, as contrasted to a long-term average.

DISCHARGE OF SNOWMELT

The amount of snow melted does not correlate directly with discharge, since not all melted snow becomes surface runoff. The following factors may account for this difference:

- Evaporation (liquid to gas) and sublimation (solid to gas) processes that transfer snowpack moisture directly to the atmosphere.
- Wind, which can accelerated evaporation.
- Rate of infiltration, which may be reduced if the ground is frozen.

Stream Gaging System and Hydrograph Data

In order to quantify the duration of the snowmelt season, streamflow hydrographs, records of snow on the ground, and calculated melting degree-hour days were inspected. The traces in Figure 3 (pages F3-1 through F3-11) show daily melting degree-hours and snow on the ground (both as measured at Anchorage International Airport) and, for gauged periods, streamflow on Chester Creek (in central Anchorage). Streamflow hydrographs for long periods of record are only available on stream systems that originate in the Chugach Mountains east of Anchorage. Streamflow in these systems is characterized by a year-round baseflow, urban snowmelt in March and April and snowmelt from higher elevations from

April through June. For this analysis, daily stream flow data for two stations on Chester Creek, which flows through a highly urbanized area of Anchorage, were used.

Snowmelt-Producing Discharge

Care must be taken in interpreting streamflow hydrographs to distinguish the onset of urban snowmelt runoff from snowmelt at higher elevations. In fact, these time periods often overlap. In some years, urban runoff is small to non-existent due to lack of snow at lower elevations, while large amounts of streamflow may results from snowmelt at higher elevations. There is a large year-to-year variability in these data, as can be seen in Figure 3.

Dates for the onset and cessation of urban meltwater discharge were estimated based on these considerations (Table 8). Spring snowmelt discharges can start as early as February 3 and last as late as April 16. The average duration, based on records of declining levels of snow on the ground, is 30 days.

Table 8
SNOWMELT DISCHARGE SEASON

Water Year	Begin date	End date	Duration - days	Snow year ranking, percent	Total snowfall, ft
1954	No gage data	4/13		18	4.1
1955	No gage data	5/6		100	11.1
1956	No gage data	4/27		98	10.7
1957	No gage data	4/5		48	5.6
1958	No gage data	3/2		0	2.5
1959	3/23	4/26	34	89	7.9
1960	3/5	4/15	41	77	6.8
1961	3/16	3/30	14	5	3.2
1962	4/1	4/5	4	61	6.2
1963	3/5	4/25	51	80	7.1
1964	2/5	4/22	76	34	4.9
1965	2/28	3/26	26	70	6.5
1966	4/1	4/18	17	84	7.5
1967	3/1	4/14	44	64	6.2
1968	3/29	4/12	14	68	6.5
1969	3/22	4/12	21	23	4.7
1970	3/16	3/18	2	9	3.5
1971	4/4	4/22	18	32	4.9
1972	3/22	5/5	44	66	6.3
1973	3/16	4/12	27	16	3.9
1974	3/15	3/29	14	27	4.8
1975	4/5	5/2	27	82	7.3
1976	4/16	4/19	3	39	5.1
1977	No distinct hydrograph rise	4/18		20	4.4
1978	3/29	4/9	11	30	4.8
1979	3/11	4/14	34	86	7.6
1980	2/3	3/24	49	52	5.7
1981	3/6	3/11	5	2	2.7
1982	2/3	3/18	43	11	3.7
1983	3/12	3/28	16	57	6.0
1984	3/3	4/11	39	75	6.7
1985	2/24	4/26	61	36	5.1
1986	3/3	4/18	46	14	3.8
1987	No gage data	3/26		7	3.2
1988	2/17	4/18	60	73	6.7
1989	3/20	4/3	14	41	5.3
1990	2/26	4/11	44	93	8.5
1991	2/23	4/15	51	43	5.5
1992	3/26	4/16	21	91	8.3
1993	3/11	4/12	32	59	6.0
1994	No gage data	4/10		45	5.5
1995	No gage data	4/16		95	10.1
1996	No gage data	3/11		55	5.8
1997	No gage data	4/3		50	5.6
1998	No gage data	3/23		25	4.8
avg	3/11	4/9	30		
max	4/16	5/6	76		
min	2/3	3/2	2		

Begin date – based on hydrograph inspection
End date – based on snow on the ground data

Rainfall

Rainfall is precipitation that falls as rain. In Anchorage, this can occur in any month of the year.

MONTHLY RAINFALL AMOUNTS

Rainfall occurs primarily April through October, although events of winter rain on snow do occur. During the summer months (May through September), rainfall is lowest in May and June (0.6 and 1.0 inches respectively), increasing through July; August and September receive the largest amount of rainfall (Table 1).

RAIN STORM ANALYSIS ON SEASONAL BASIS

Rainfall was analyzed for the summer season (May through September) in a similar manner to the analysis of storm events for the entire year. The following criteria were assigned to allow SYNOP to determine a discrete storm event:

- Precipitation volume was not limited; that is, any rainfall greater than zero was included in the analysis.
- May 1 through September 31, the timeframe used for precipitation.
- An inter-event time was determined, based on the lowest inter-event time that produced a series of time-between-storms ("deltas"), whose coefficient of variation was approximately 1, as recommended in the SYNOP documentation. For storms with no minimum volume, an inter-event time of 11 hours was specified.

For volumes greater than 0.0 inches, SYNOP found 845 total storms for the 106 months analyzed. These storms had an average duration of 11 hours and average volume of 0.20 inches, as shown in Table 9.

Table 9
SUMMER RAINFALL STATISTICS BY STORM

Storm	Number of events	Total	Minimum	Maximum	Average	Coefficient of variation
Duration (hours)	845	9379	1	92	11.1	1.1
Intensity (inches per hours)	845	15.9236	0.0022	0.37	0.0188	1
Volume (inches)	845	170.73	0.01	2.61	0.2	1.4
Delta[1] (hours)	821	72411	12	795	88.2	0.99

[1] Delta is the length of the period between storms. The period between the last storm of one year and first storm of the next year is not included.

Annual statistics were also derived for the 19 years that had 5 complete months of summer rainfall events (Table 10). An average of 40 rainfall events per summer were identified, with a mean annual duration of 441 hours and a mean annual volume of 7.97 inches.

Table 10
ANNUAL SUMMER RAINFALL EVENT STATISTICS FOR YEARS WITH FIVE MONTHS OF RAINFALL DATA

	Total	Minimum	Maximum	Average
Number of Storms	756	25	57	40
Annual Volumes (inches)	151	4.29	13.14	7.97
Annual Duration (hours)	8384	190	688	441

RAINFALL AMOUNTS PRODUCING DISCHARGE

Rainfall intensity and antecedent conditions affect the amount of storm water that will be discharged from a given storm volume. Low intensity rainfall is less likely to run off than high intensity rainfall. Dry periods preceding storm events will lower the groundwater table and dry out depressed areas, increasing rainfall interception and infiltration and decreasing rainfall runoff. Conversely, runoff will be higher from rainfall on surfaces already holding ponded and infiltrated water.

ANALYSIS OF RECURRENT 6-HOUR STORMS

The SYNOP analysis produced a series of storm events of variable duration and volume. From this series of rainfall events, 35 events of 6-hour duration were extracted. Statistics for the 35 events are shown in Table 11. A histogram of the frequency of each 0.02-inch increment of rainfall volume, from 0.02 to 0.40 inches, is shown in Figure 4.

Table 11
STATISTICS OF 6-HOUR RAINFALL EVENTS

Statistic	Value	Units
Mean	0.12	inches
Median	0.1	inches
Mode	0.08	inches
Standard Deviation	0.10	inches
Kurtosis	0.7	inches
Skewness	1.25	inches
Range	0.37	inches
Minimum	0.02	inches
Maximum	0.39	inches
Number of storms	35	storms

Assumptions

In order to perform the analysis of defining 2-year and 10-year recurrent 6-hour storms, the following assumptions were made about the storms extracted from the SYNOP output:

- The storms are homogeneous. That is, they arise from similar meteorological events. However, this may not be true for data spanning the 5 summer months, since seasonal meteorological effects may differ from May through September. It may also not be true for infrequent and frequent storm events, since infrequent events may be the result of different meteorological factors than cause more frequent events.
- Each storm is independent of other storms. That is, the storm duration and volume are not influenced by preceding storms and do not influence subsequent storm events. This may not be true for these 6-hour events (i.e., there may be some serial effects or causes). However, the use of inter-event times, which produce time-between storm-series with a coefficient of variation close to 1 are meant to isolate storm events.
- The storm events are stationary. That is, they are measured at the same place and under climatic conditions that are stationary throughout the 26-year period.

Analysis Method

The partial-duration series method of analysis was used to determine 2-year and 10-year storms. The annual maximum and minimum series were also analyzed for comparative purposes.

The partial-duration series method involves selecting values for a given event type (in this case, the volume of 6-hour storms) above a given threshold from all years of record. For the annual duration series, a single annual value is selected, such as the highest or lowest above a given threshold, for a given event type for each year of record. The greater number of data points in a partial-duration series is an advantage over the annual series when the period of record is short. The partial-duration series also yields a greater number of lower values than does the annual series. Analyses of these different series yield similar results for very large events; for smaller events of shorter recurrence intervals, the annual duration series may under-predict the value (Langbein, 1949).

The partial-duration series method was selected for this analysis, because the values for the short recurrence intervals (2 and 10 years) of the events are of interest. Two annual series, made up of the smallest and largest annual 6-hour storms, were also analyzed for comparison.

The partial-duration series analysis involved the following steps (Langbein, 1949):

1. Determine the number of years of record, N. For this series, N = 21. (Although there were only 19 years with complete records for all 5 months, each month was represented an average of 21 times [Table 3]).
2. Select all events above a given threshold. This will yield nN events (where n is the average number of events per year), each with a value x_i, i = 1 to nN. All 6-hour rainfall events, with volumes greater than 0.01 inches, were included in the analysis. The total number of rainfall events is nN=35, yielding n=1.7 events per year.
3. Order the events by magnitude of x_i from largest to smallest, and assign each a rank, m, where m=1 corresponds to the event with the maximum magnitude. In this analysis, 0.39 inches was the maximum volume of a 6-hour storm.
4. Determine the expectancy, P_E, of each event not being exceeded in the series, $(X>x_i)$, using the Cunnane plotting position: $P_E = \frac{(m-0.4)}{(N+0.2)}$. This plotting position was used because it can be applied to several different assumed distributions (Reich, et al., 1981). In the range of interest (2-year to 10-year storms), the Gumbel plotting position would have yielded nearly identical results.
5. Convert the expectancy to the probability, P, that the event will be exceeded on an annual basis, $(X<=x_i)$: $P = e^{-P_E}$.
6. Determine the recurrence interval $T = \frac{1}{(1-P)}$, for all events greater than x_i.
7. Plot n(T) versus x for all nN=35 values of x_i.

The annual series analysis involved the following steps:

1. Create two series by selecting the maximum and minimum event for each year. For each series, this will yield N events (where N is the number of years of record), each with a value x_i, i = 1 to N. Only 14 years had at least one 6-hour event. Three years had only one 6-hour event; those events were used in both the annual maximum and minimum series.
2. Order the events by magnitude, from largest to smallest, and assign each a rank, m, m=1 to 14.
3. Determine the probability, P, that the event of magnitude x_i is not exceeded on an annual basis, $(X<= x_i)$, using the Cunnane plotting position: $P = \frac{(m-0.4)}{(N+0.2)}$.
4. Determine the recurrence interval, $T = \frac{1}{(1-P)}$, for all events with a magnitude greater than x_i.
5. Plot ln(T) vs. x for all N=14 values of x_i.

The ranking of rainfall event volumes for all 35 storms is shown in Figure 5. The numeric results for the estimated recurrence intervals of each of the series types (one partial-duration and two annual series), are shown in Tables 12 and 13. Figure 6 shows the partial-duration series and the annual maximum and minimum series; as expected, the annual minimum and maximum series bracket the plotted position of the partial-duration series.

Table 12
PARTIAL-DURATION SERIES OF 6-HOUR STORM EVENTS BASED ON VOLUME

Volume, in x_i	Rank m	Expectancy P_E	Probability of non-exceedence $P(X<x_I)$	Recurrence interval, years $T = 1/(1-P)$
0.39	1	0.03	0.97	35.54
0.35	2	0.08	0.93	13.64
0.31	3	0.12	0.88	8.59
0.3	4	0.17	0.84	6.35
0.27	5	0.22	0.80	5.09
0.25	6	0.27	0.77	4.28
0.22	7	0.31	0.73	3.71
0.16	8	0.36	0.70	3.30
0.16	9	0.41	0.66	2.98
0.15	10	0.46	0.63	2.73
0.14	11	0.50	0.60	2.52
0.12	12	0.55	0.58	2.36
0.12	13	0.60	0.55	2.22
0.12	14	0.65	0.52	2.10
0.11	15	0.69	0.50	2.00
0.1	16	0.74	0.48	1.91
0.1	17	0.79	0.45	1.83
0.1	18	0.84	0.43	1.76
0.09	19	0.88	0.41	1.70
0.08	20	0.93	0.39	1.65
0.08	21	0.98	0.38	1.60
0.08	22	1.03	0.36	1.56
0.08	23	1.08	0.34	1.52
0.07	24	1.12	0.33	1.48
0.06	25	1.17	0.31	1.45
0.05	26	1.22	0.30	1.42
0.05	27	1.27	0.28	1.39
0.04	28	1.31	0.27	1.37
0.04	29	1.36	0.26	1.34
0.04	30	1.41	0.24	1.32
0.03	31	1.46	0.23	1.30
0.03	32	1.50	0.22	1.29
0.02	33	1.55	0.21	1.27
0.02	34	1.60	0.20	1.25
0.02	35	1.65	0.19	1.24

Table 13
ANNUAL MAXIMUM AND MINIMUM SERIES OF 6-HOUR STORM EVENTS BASED ON VOLUME

Minimum annual volume inches	Maximum annual volume inches	Rank m	Probability of exceedence, 1-P(x < X)	Recurrence interval, T = 1/(1-P) years
0.16	0.39	1	0.042	23.67
0.1	0.35	2	0.113	8.88
0.09	0.31	3	0.183	5.46
0.08	0.3	4	0.254	3.94
0.08	0.27	5	0.324	3.09
0.08	0.16	6	0.394	2.54
0.07	0.16	7	0.465	2.15
0.04	0.15	8	0.535	1.87
0.04	0.12	9	0.606	1.65
0.03	0.12	10	0.676	1.48
0.03	0.1	11	0.746	1.34
0.02	0.09	12	0.817	1.22
0.02	0.08	13	0.887	1.13
0.02	0.05	14	0.958	1.04

Plotting allows graphical interpretation of the data. If the resulting plots can be made linear, either graphically or by mathematical curve-fitting, values for the recurrence intervals of interest can be estimated. The graphical method involves drawing the line of best fit, by eye, through the points, and reading the recurrence interval and corresponding rainfall volume directly from the plot. Mathematical curve-fitting can be performed independently of data plotting, but plotting allows a visual check data fit. If the empirical plotting method produces a strong linear fit, then mathematical curve-fitting, by use of linear regression, is indicated as an appropriate method of determining the volume of rain for a given recurrence interval. Linear regression also provides a measure of the fit of the derived line to the data points through the coefficient of determination, r^2, which is a measure of the ability of the regression line to explain variations in the dependent variable (in this case, the natural logarithm of the recurrence interval).

Results

As can be seen in Figure 6, the plot of the partial-duration series yields a fairly linear plot in the region of interest, between 2 and 10 years. Linear regression was used to fit a line to the data points between the recurrence intervals of 1.3 and 13.6 years. The result was the equation:

$$\text{volume of rainfall (inches)} = 0.00735 + 0.145451 * \ln (\text{recurrence interval (years)})$$

The coefficient of determination, r^2, for the fit of the line, based on the 30 data points in this range, is 0.97, indicating that 97 percent of the variation in rainfall volume is explained by the regression equation. That is, 97 percent of the variation of dependent results (rainfall volume) results from variation of the independent variable (the natural logarithm of the recurrence interval). Based on this fitted line, the rainfall volumes for the desired storms were calculated:

Table 14
RAINFALL VOLUMES FOR DESIRED STORMS

Recurrence Interval, years	Estimated Rainfall Volume, inches
2	0.11
10	0.34

These estimated volumes are lower than current MOA Department of Public Works criteria, which specify a volume of 0.66 inches for a 2-year 6-hour storm and 1.06 inches for a 10-year 6-hour storm (DPW, 1988).

Typical Climate Conditions

For purposes of modeling storm water quality and quantity, the period of record was examined to find 1 or more years that represent "typical" climate conditions. A variety of inter-related climate conditions were compared against long-term averages, including:

- Number of melting degree-hour days with snow on the ground from March 1 to April 15
- Begin and end dates of snowmelt
- Summer rainfall amounts and average storm volume and intensity
- Winter snowfall

A ranking for each variable for each year (October through September) was assigned, based on the range of values over the years of record. For each year for which all these variables were available, a composite ranking was determined by averaging the individual rankings for each variable. Results are shown in Figure 8. Only 18 out of the 45 years from 1954 through 1998 had data for all seven variables. Theoretically, the "typical" year will have a composite ranking of 50 percent and individual rankings that are well-balanced. The years 1965, 1966, 1978, and 1981 have composite rankings of between 45 percent and 55 percent. Of these, 1978 appears to have the most balanced values for each individual parameter. This model could be adapted to provide greater weight to specific variables of interest. Currently the year 1966 is being used as a standard median year for precipitation and temperature conditions. (Daily data for 1966 are included in Appendix A).

Alternatively, a synthetic year could be constructed. However, due to the interdependence and serial correlation of daily climate conditions, this approach is considerably more complex.

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Anchorage Hydrology

Anchorage storm drainage systems carry a combination of stormwater and groundwater. This section describes some of the underlying hydrologic conditions that affect flows in the storm drainage system.

Groundwater Conditions influencing Storm Drainage

The Anchorage Bowl and other areas within the MOA have relatively high groundwater tables. Anchorage is built over and along margins of a relatively flat, glacial estuarine basin originally covered by extensive wetlands and drained by small bog creeks. Groundwater infiltration of storm sewers and drainage systems specifically designed to lower high groundwater tables in this naturally wet terrain are common throughout much of the Anchorage Bowl. In addition, storm drainage system piping is generally buried at depths of 3 or more feet to prevent freeze-up and frost-heaving. The combination of high groundwater table and buried pipe leads to interception of groundwater by these systems, resulting in continual small discharges at outfalls.

This was illustrated during field screening performed from May 26 to June 11, 1992. As indicated in the preceding section, and shown in Figure 1, May and early June represent periods of no snowmelt runoff and low rainfall. However, of the 147 discharge sites visited during screening, 104 were observed to be flowing, with a median flow of about 60 gallons per minute. The majority of discharges suggest shallow groundwater discharges from large drainage basins or water naturally exiting along ground water discharges zones. The MOA-wide median conductivity value for these discharges supports the conclusion that outfall flows are significantly generated by groundwater infiltration (MOA, 1992b).

Groundwater supports base flow in the creeks that flow through the Municipality; thus streamflow records can be used to identify corresponding periods of low flow in the storm drainage system. Figure 7 illustrates the annual average flow in a creek in an urbanized area of Anchorage. While this gage reflects both base flow and storm runoff, two periods predominated by base flow can be seen: a winter period (November through March) and an early summer period (mid May through mid June).

The winter period is largely a reflection of lack of precipitation runoff due to freezing temperatures. Average daily temperatures are below freezing and little surface runoff occurs. The early summer period reflects conditions after snowmelt discharges have receded and before late summer precipitation begins.

Two corresponding wet periods occur from April through mid-May and from July through October. The high groundwater table and its direct discharge into the storm sewer system tend to extend periods of high flows due directly to storm water runoff and indirectly to interflow, the discharge of groundwater from the rising water table. Interflow moves more slowly than surface runoff but may be larger in quantity where soils are permeable and/or storms are of moderate intensity (Linsley, et al., 1982). Permeable soils and high groundwater in some areas of Anchorage coupled with relatively low intensity rainfall events (Table 9) tend to increase the proportion of rain that is intercepted by storm drains as interflow rather than surface runoff. This can be seen in Figure 7, where the 1978 trace (July-August) shows a 14 day lag between a peak runoff event and the subsequent return to base flow conditions. Because of the frequency of storms from July through October, base flows may not recede to their dry period conditions during the short periods (average of 3.7 days, Table 9) between rainfall events. This effect is not as pronounced during the April to mid-May snowmelt period, reflecting the lack of infiltration of snowmelt and reduced contributions of recharge to the shallow water table at that time of year.

Effect of Temperature on Storm Drainage

Glaciation of creeks and storm drain systems occurs frequently in the winter in Anchorage. Glaciation occurs when groundwater above freezing temperatures is discharged to the surface, where it cools. If flow velocities are low or air temperatures are sufficiently cold, the cooling water freezes. Over the course of the winter, this process can produce buildups of ice at critical points in the drainage system where flows may spread out, slow down and freeze, such as at outfalls from storm drainage systems with a high contribution of groundwater.

Anchorage Dry and Wet Weather Periods

This review of Anchorage climate characteristic may aid decision-makers in determining a season for dry weather screening, as required by the MOA's stormwater discharge permit. This information is particularly useful since many portions of the MOA's storm drainage system convey interflow and base groundwater flow in addition to surface runoff. Since this is the case, not all flows in the storm drainage system are attributable to wet weather. Interpretation of screening data in any given storm drain system should allow for consideration of groundwater inflow. Wet and dry weather periods are best described both by actual precipitation patterns and the runoff associated with rainfall and snowmelt.

Anchorage precipitation/runoff seasons can be roughly broken down into four annual periods.

1. The summer rainfall season, from July through mid-October, typically experiences prolonged rainfall events (average duration of 11 hours, Table 9) with short inter-event (dry) intervals (average duration of 3.7 days). Flows in storm drains during inter-event periods include interflow (the discharge of water from the rising groundwater table), which is not representative of dry weather conditions.

2. The winter period, mid-October through early March, is characterized by precipitation as snowfall, with little runoff due to cold conditions. Snow that falls during this period generally does not melt and run off until spring. These conditions negatively affect the efficiency and practicality of dry weather screening, due to cold temperatures and icing conditions at storm drain outfalls.

3. The spring period, from early March through mid- to late April, is normally distinguished by warming temperatures resulting in the runoff of snowmelt. Runoff occurs first from surfaces hydraulically connected to the storm drainage system and somewhat later from tributary landscaped and undeveloped areas. This melt is driven by a variety of factors, predominated by warm temperatures. However, the pattern is variable over the period with a series of warm days producing large amounts of melt water interspersed by cooler days during which little melt occurs.

4. The early summer period, from late April through June is the period of low precipitation, and that precipitation generally falls as rain. These months, on average, have somewhat fewer storms of lower intensity and shorter duration than the months of July through October. Based on these factors and compared with other periods of the year, the early summer period provides best chance for successful dry weather screening of storm drain discharges.

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Figure 1 Anchorage Weather Daily Averages

Figure 2 Average Melting Degree-Hours per Day

Figure 3 Daily Degree-hours, Snow on the Ground, and Streamflow during First Quarter by Year

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Figure 4 Histogram of 6-Hour Rainfall Volumes at AIA

Figure 5 Ranking of 6-Hour Storm Volumes at AIA

Figure 6 Recurrence Intervals and Volumes for 6-Hour Storms at AIA

Figure 7 Average Daily Air Temperatures and Average Daily Flows - Chester Creek at Arctic Boulevard (1966-1993)

Figure 8 Year Ranking by Seven Climate Characteristics

Appendix A
1966 Daily Climatological Data