A Report on a Statistical Model to Forecast Seasonal Inflows to Cowichan Lake

Prepared by:
Allan Chapman, MSc, PGeo
Hydrologist, Chapman Geoscience Ltd., and Former Head, BC River Forecast Centre
Victoria BC
February 6, 2011

Introduction

At the request of the BC Conservation Foundation (BCCF), an effort began in early 2010 to develop a statistical model to provide forecasts of seasonal inflows to Cowichan Lake. The purpose of the statistical model is to provide quantitative forecasts of seasonal inflows to Cowichan Lake based on available data, to assist Catalyst Paper (which owns and operates the weir at the outlet of Cowichan Lake) and a committee of water management stakeholders with in-season decision-making with respect to lake levels and maintenance of flows in the Cowichan River downstream of Cowichan Lake for the benefit of a wide range of community interests and resource values. Allan Chapman began the model development project while serving as Head of the BC River Forecast Centre (RFC), and completed the project subsequent to departing the RFC. This report summarizes the model, which is available in stand-alone Excel format.

Data and Model Development

A statistical model operates on the basis of making estimates of an outcome for a dependant variable (in this case, various configurations of seasonal volume inflow to Cowichan Lake) based on values of independent predictor variables. The data used for the model are as follows:

Inflow Data: Measurements of inflow to Cowichan Lake were calculated based on daily data from two Water Survey of Canada stations:

- Cowichan Lake Near Lake Cowichan (08HA009);
- Cowichan River at Lake Cowichan (08HA002).

Inflows for every day for the period of record (up to 2008) were calculated as the sum of daily changes in water volume in the lake (calculated from the change in water level as measured by gauge 08HA009) and the daily outflow from the lake (as measured by gauge 08HA002). The daily inflows were then summed into monthly values for every year for the period of record, and then further summed into various “seasonal” amalgamations for the purpose of the statistical modeling.

The inflow data were amalgamated into the following eight time periods for statistical analysis:

- March – September;
- April – September;
- May – September;
- June – September;
- March – June;
- April – June;

- May-June;
- June.

Independent or Predictor Variables: An array of independent data was acquired to explain the seasonality of runoff into Cowichan Lake, including climate, snow survey, and antecedent inflow data, and data on large scale telekinections (i.e., Pacific Decadal Oscillation, El Niño Southern Oscillation). The data are:

- Lake Cowichan (station 1012055) - monthly precipitation and temperature (1961-2008).
- Cowichan Lake Forestry (station 1012040) – monthly precipitation and temperature (1955-2008).
- Jump Creek automated snow pillow (3B23P) – 1st of month observations of snow water equivalent (Jan 1st, Feb 1st, Mar 1st, Apr 1st).
- Mt Cokley snow course (3B02) – 1st of month observations of snow water equivalent (Mar 1st, Apr 1st, May 1st. (The Mt. Cokley snow course was located slightly north-east of Port Alberni, and was the only manual snow measurement operated by the Ministry of Environment on south Vancouver Island. The Ministry of Environment discontinued this snow course following the 2009 season.)
- Heather Mountain snow course (3B13) - 1st of month observations of snow water equivalent (Mar 1st, Apr 1st, May 1st) for the period of record (1959-1991). (The Heather Mountain snow course was located in the Cowichan Lake valley, at the north-east end of the lake. It was discontinued by the Ministry of Environment in 1991.)
- Antecedent Inflow - calculated from the monthly inflow data acquired for the Inflow Data listed above.
- Telekinections – various large scale telekinections are known to influence climate and weather on south Vancouver Island, including the Pacific Decadal Oscillation (PDO) and the El Nino Southern Oscillation (ENSO). The PDO produces multi-decadal periods of warm/cold and dry/wet weather, while ENSO produced similar effects but cycling over shorter time periods of a few months to a year. Both are related to periodicity of ocean temperature changes in the equatorial and north Pacific Ocean, and the effects of those ocean temperatures on the air masses moving over southern Vancouver Island. A number of specific variables were selected for analysis:
    - PDO;
    - NIN1+2 – an ENSO index;
    - NIN03 – an ENSO index;
    - NIN04 – an ENSO index;
    - NIN3.4 – an ENSO index;
    - Multivariate ENSO Index (MEI).

  The data were compiled in monthly time steps for the 1955-2008 period, and then summarized into averages for the winter season of Oct-Feb, Oct-Mar and Oct-Apr for statistical analysis.

Statistical Analysis

The data sets were compiled into an Excel spreadsheet, and were analyzed using Systat v.13. The statistical significance of the various independent variables with the seasonal inflow data were assessed using Pearson correlation analysis. Following the correlation analysis, detailed multiple regressions were evaluated using a stepwise linear regression technique. In most cases, independent variables with $p < 0.05$ were retained in the multiple regressions. In some cases (particularly with the analysis of the Jump Creek snow data), variables were forced into the model with a significance somewhat poorer than 5%.

The following variables were the most significant predictors of the seasonal Cowichan Lake inflows:

- Antecedent discharge for the Oct-Feb period;
- Antecedent precipitation for the period October to the month prior to the forecast period (e.g. Oct-Feb; Oct-Mar; Oct-Apr; Oct-May);
- Precipitation for the period beginning with the forecast month, and ending in either September or June, depending on the forecast period;
- Average June temperature (Interestingly, June temperature has a much higher correlation with inflows than does either July or August temperature. I hypothesize this is because water available for evaporation from the terrestrial part of the basin is much higher in June than in July or August, and June temperatures, therefore, have a more significant effect on the terrestrial hydrologic cycle);
- Multivariate Enso Index. The PDO and various other ENSO indices are all strongly correlated to inflows, but the MEI is the most significant, presumably because it captures the main causative factors from the other indicators.

Results

The results are organized in the spreadsheet titled “Cowichan Inflow Program.xls” (in Excel 97-2003 format). In the spreadsheet are eight (8) work sheets. Four (4) of the worksheets contain the various models. They are:

- Forecast – March;
- Forecast – April;
- Forecast – May;
- Forecast – June.

Each of these worksheets contains four separate multiple regression models for the period beginning with the month in question and ending in either September or June:

- March – September Equation 1 (based on precipitation data);
- March – September Equation 2 (based on snow data);
- March – June Equation 1 (based on precipitation data);
- March – June Equation 2 (based on snow data).

For the forecasts done for the March – September and March – June periods, the data for the various predictor variables are entered into the worksheet, and the resultant forecasts are shown. Inflow forecasts are shown in units of cubic decameters ($kdam^3$) – one (1) $kdam^3$ is equal to one million (10^6) cubic metres of water. For each forecast equation, the R^2 (i.e., the proportion of variability in the data set that is accounted for by the statistical model) and the standard error of the estimate are listed.

Four (4) other worksheets in the Excel file contain all of the raw data for the 1955-2008 period, and show the results of applying the equations to the data for each individual year. This is useful in helping evaluate the uncertainty in the forecast equations. These worksheets are titled:

- Data – March
- Data – April
- Data – May
- Data – June

Brief Summary of Cowichan Lake Inflows

Monthly and annual inflows to Cowichan Lake for the 1955-2008 period are shown in Table 1 and Figure 1. Average annual inflow was 1,438 $kdam^3$ (1,438,000,000 m^3). This corresponds to an average annual runoff of 2,411 mm. With an average annual evapotranspiration estimated to be about 600 mm, this indicates that average annual precipitation in the Cowichan Lake basin is about 3 metres (3,000 mm), which is very wet.

Although annual inflows are very high, there is a very strong seasonality, with a distinctly wet winter and a distinctly dry summer. Almost 50 percent of the inflow to the lake occurs during November, December and January, whereas only 3 percent of the inflow occurs during July, August and September.

Annual inflows are variable, ranging from a low of 919 $kdam^3$ (1977) to a high of 2,026 $kdam^3$ (1974). However, even in 1977 (the driest year of record since 1955), the Cowichan Lake basin was still “wet”, with annual runoff of over 1,500 mm and an estimated annual precipitation of over 2,000 mm. For annual inflow, the standard deviation is only 20 percent of the mean value. The same inter-annual consistency does not hold true for the summer runoff. For July-September runoff, the standard deviation is 75 percent of the mean value, indicating there is much greater variability among the years of record. The summer of greatest runoff was 1997 (255 mm runoff), while 1985 had the lowest runoff (of only 4 mm). The data suggest that runoff into Cowichan Lake during summer has become much more variable since about 1995, with five out the seven driest summers of record occurring since 1995, including 2003 and 2006, which were the 2nd and 3rd driest summers of record, respectively. Figure 2a depicts the trend in annual inflow (measured through the hydrologic year of October–September) and Figure 2b depicts the trend in summer inflow (June–September), over the 1955-2008 period. Although there is a slight downward trend in annual inflow to Cowichan Lake since 1955, the magnitude is small and the trend is not statistically significant. However, the downward trend in summer inflow is statistically significant, and has a large magnitude. During the late 1950s, summer inflow averaged about 104 million cubic metres. By 2008 it had dropped to an average of 68 million cubic metres, an annual reduction of 35 percent. The causes of this are beyond the scope of this study, but they are thought to be largely climatological in origin. The shift in the Pacific Decadal Oscillation from the cold phase to the warm phase in 1976 has a strong statistical effect. Also, it has been well documented for the Pacific Northwest (including Vancouver Island) that there has been a downward trend in peak winter snow accumulation over the last few decades, attributed to “climate change” by some authors.

It is evident that the Cowichan Lake basin has been blessed with abundant natural water supply when measured over an annual cycle, but that it frequently has very limited natural summer water supply. A strategy to address this seasonal imbalance would be to increase the storage of water in Cowichan Lake, to provide for increased releases into the Cowichan River below the lake during dry summers when and as needed. As an example, an increase in live storage of 30 cm on the lake would create storage of about 18.6 million m^3 of water, which would allow for significant increases in the summer discharge and water level on the Cowichan River, relative to what has occurred during the low flow years of the recent record. This augmented storage, however, would make up only about one-half of the reduction in summer inflows that has occurred since 1955.

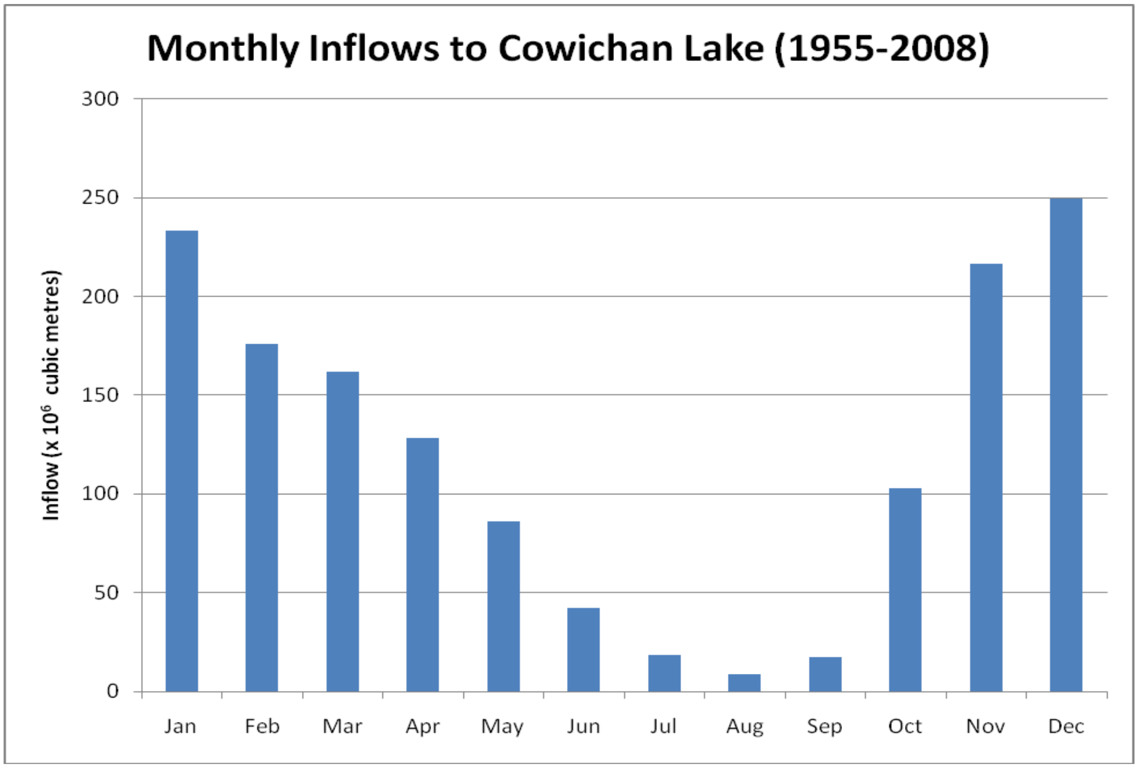

Figure 1a. Monthly inflow to Cowichan Lake

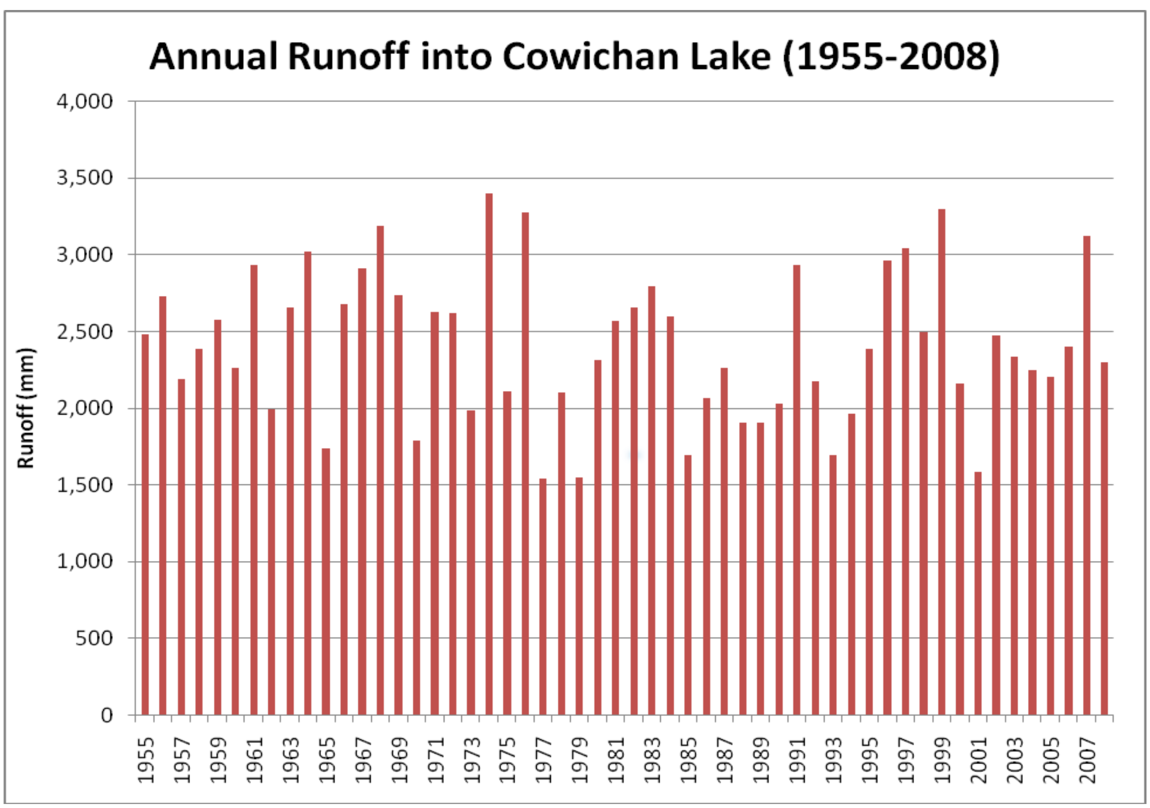

Figure 1b. Annual runoff (mm) into Cowichan Lake

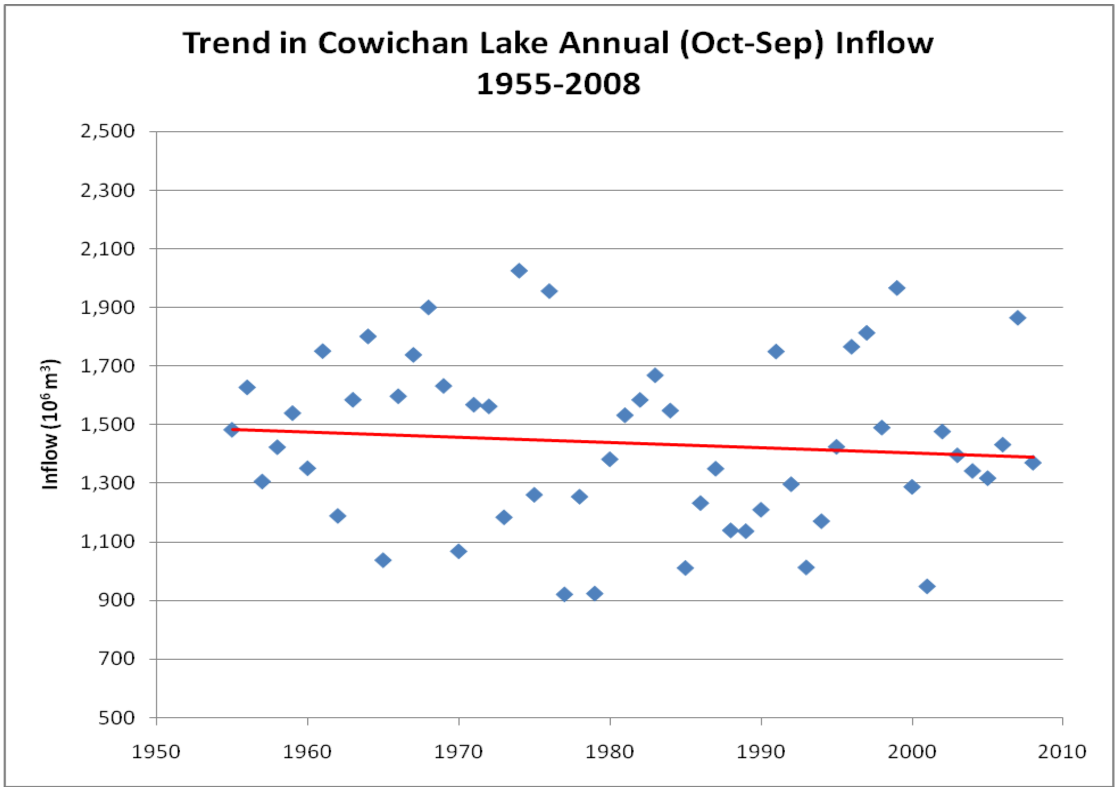

Figure 2a. Trend in Cowichan lake annual inflow, 1955-2008

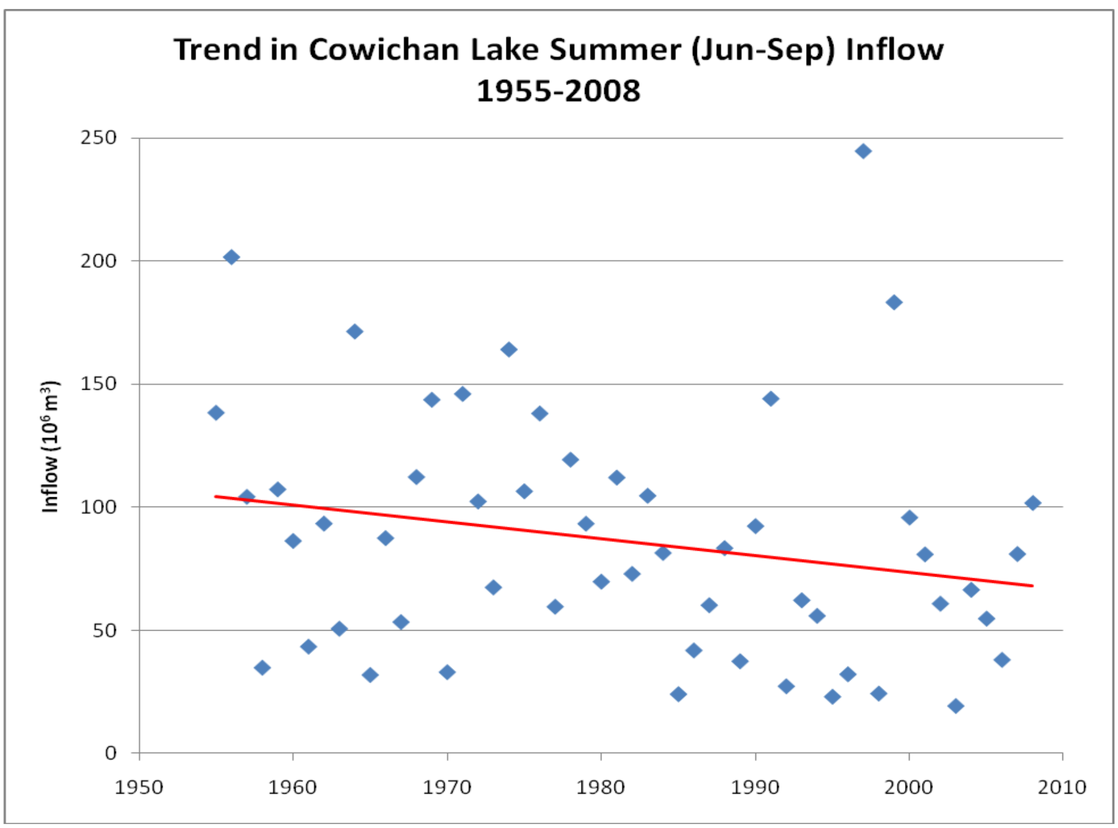

Figure 2b. Trend in Cowichan Lake summer inflow, 1955-2008

Table 1. Net Inflows to Cowichan Lake, 1955-2008. Units are kdam^3 (1000*decametre), or 10^6 cubic metres

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Inflow (Oct-Sep)	Annual Runoff (mm)	% of Average	Rank (out of 54 yrs)	Jul-Sep Runoff (mm)	% of Average	Rank (out of 53 yrs)
1954							44.4	15.1	27.9	105.4	392.1	284.2							
1955	137.1	85.9	63.8	171.3	103.9	72.9	36.5	19.5	9.4	153.9	296.6	180.4	1,482	2,487	103%	31	110	149%	42
1956	175.1	63.0	157.5	207.7	191.2	137.2	39.5	3.5	21.3	197.5	118.9	298.1	1,627	2,730	113%	41	108	147%	40
1957	69.9	136.7	171.9	149.7	58.3	20.2	30.0	28.1	25.8	51.8	80.8	309.3	1,305	2,190	91%	19	141	192%	49
1958	420.9	270.5	90.5	122.7	41.3	13.0	0.6	-1.8	23.1	89.4	194.0	353.4	1,423	2,387	99%	27	37	50%	19
1959	276.9	63.3	156.9	171.0	126.7	54.4	12.2	4.2	36.5	65.2	156.3	213.0	1,539	2,582	107%	34	89	121%	37
1960	168.1	219.5	126.9	205.1	110.1	58.9	8.5	5.9	13.0	115.0	175.2	201.0	1,351	2,266	94%	23	46	62%	23
1961	437.4	371.7	206.6	110.5	90.1	19.9	8.6	2.3	12.5	118.4	159.4	238.9	1,751	2,938	122%	46	39	54%	21
1962	209.2	88.3	68.5	120.2	91.4	40.5	10.1	23.3	19.4	142.0	332.9	332.4	1,188	1,993	83%	12	89	121%	36
1963	132.1	256.3	129.9	127.5	80.7	14.0	23.6	8.2	4.8	216.5	317.2	313.7	1,584	2,659	110%	39	62	84%	27
1964	263.0	157.4	147.3	115.8	99.1	71.5	49.0	17.0	33.8	85.6	112.4	139.8	1,801	3,022	125%	48	167	228%	51
1965	136.7	232.0	93.5	122.7	81.8	19.6	3.8	5.9	2.5	170.1	226.5	272.5	1,036	1,739	72%	6	21	28%	8
1966	299.4	135.0	195.2	134.5	76.2	49.0	24.7	3.6	10.1	97.4	204.5	476.1	1,597	2,679	111%	40	64	88%	29
1967	327.3	189.6	205.3	78.1	106.5	39.5	8.3	-0.6	6.2	284.6	140.1	306.6	1,738	2,916	121%	44	23	32%	9
1968	437.3	248.9	209.2	95.0	66.4	34.9	17.2	15.6	44.4	212.5	226.7	253.5	1,900	3,188	132%	51	130	176%	48
1969	92.9	97.5	184.3	239.9	181.1	57.6	12.8	7.5	65.7	78.4	126.3	220.2	1,632	2,738	114%	42	144	196%	50
1970	161.7	127.2	118.7	154.5	46.8	12.3	3.8	-0.1	17.0	65.2	144.2	220.2	1,067	1,790	74%	7	35	47%	17
1971	279.3	217.0	178.0	149.0	168.9	80.7	34.0	8.0	23.2	101.5	249.2	109.0	1,568	2,630	109%	37	109	149%	41
1972	177.4	238.0	333.3	148.8	102.7	39.0	37.5	3.8	22.1	7.1	122.0	352.1	1,562	2,621	109%	36	106	145%	39
1973	281.6	105.7	118.7	53.5	74.9	49.3	12.7	0.4	5.0	72.9	232.2	373.8	1,183	1,985	82%	11	30	41%	15
1974	354.6	216.4	307.4	171.6	132.6	95.0	53.5	9.4	6.1	10.3	217.0	287.2	2,026	3,399	141%	54	116	158%	44
1975	153.3	85.0	159.3	97.0	144.4	54.4	13.6	24.5	13.9	281.3	432.5	300.8	1,260	2,114	88%	16	87	119%	35
1976	217.2	165.1	136.4	137.5	147.0	67.1	30.9	21.2	18.7	38.1	78.9	155.9	1,956	3,281	136%	52	119	162%	45
1977	95.0	151.2	165.5	117.0	58.4	30.1	7.6	2.1	19.8	94.5	273.6	244.4	919	1,543	64%	1	49	67%	24
1978	143.6	119.6	129.9	70.8	57.7	18.9	3.8	21.5	75.0	36.3	86.3	115.2	1,253	2,103	87%	15	168	229%	52
1979	35.2	227.8	189.6	81.3	57.3	17.5	18.5	2.3	55.0	117.7	71.2	415.5	922	1,548	64%	2	127	173%	47
1980	151.0	250.4	131.9	136.3	37.6	26.4	23.4	2.9	17.0	46.4	296.3	429.7	1,381	2,318	96%	25	73	99%	30
1981	118.8	225.6	58.7	174.8	69.5	66.1	12.2	5.4	28.2	178.6	295.3	278.0	1,532	2,570	107%	33	77	105%	31
1982	183.4	272.0	110.0	100.7	93.0	43.3	15.6	4.8	9.2	172.3	133.0	275.1	1,584	2,658	110%	38	50	67%	25
1983	284.8	379.0	206.6	74.4	38.4	29.3	53.0	8.5	13.9	35.6	429.7	99.2	1,668	2,799	116%	43	126	172%	46
1984	265.7	195.5	173.0	129.9	137.7	43.0	17.2	4.4	16.9	161.9	265.4	143.8	1,548	2,597	108%	35	64	88%	28
1985	48.5	72.8	66.4	148.6	78.3	21.9	0.6	-2.8	4.3	131.1	94.9	76.6	1,010	1,694	70%	4	4	5%	1
1986	290.5	220.8	189.6	60.1	126.0	26.7	13.0	-0.1	2.2	15.0	200.6	239.4	1,232	2,066	86%	14	25	34%	10
1987	280.7	176.9	212.3	101.0	63.1	50.0	8.8	1.0	0.4	1.3	86.6	232.6	1,349	2,264	94%	22	17	23%	5
1988	153.6	136.5	162.5	173.0	108.8	59.9	14.9	1.1	7.4	26.5	282.5	137.5	1,138	1,910	79%	9	39	53%	20
1989	206.1	81.9	148.0	166.3	49.4	17.6	12.5	6.6	0.7	67.4	178.9	164.6	1,136	1,905	79%	8	33	45%	16
1990	216.0	186.7	150.9	108.9	42.9	74.6	11.0	4.3	2.4	142.4	476.9	245.9	1,209	2,028	84%	13	30	40%	13
1991	190.1	323.8	65.4	117.1	43.8	15.1	7.9	84.6	36.4	8.6	214.5	231.2	1,749	2,935	122%	45	216	294%	53
1992	428.8	216.9	51.2	72.6	45.0	9.2	7.2	1.4	9.4	57.3	154.9	100.8	1,296	2,174	90%	18	30	41%	14
1993	122.0	69.7	189.8	158.4	96.6	45.5	10.3	6.1	0.2	16.7	52.9	262.9	1,012	1,697	70%	5	28	38%	12
1994	188.9	168.6	294.2	96.2	33.5	40.2	8.8	0.2	6.6	44.9	165.5	375.5	1,170	1,963	81%	10	26	36%	11
1995	234.3	275.2	200.0	75.4	29.9	11.5	4.5	3.8	3.2	114.0	433.9	337.8	1,424	2,389	99%	28	19	26%	6
1996	269.6	202.5	112.3	186.9	76.6	23.9	5.0	-0.6	3.8	125.0	139.8	171.1	1,766	2,963	123%	47	14	19%	4
1997	383.3	110.4	311.9	179.1	148.3	92.5	68.0	18.2	65.8	245.3	215.7	234.4	1,813	3,043	126%	49	255	347%	54
1998	344.2	207.2	138.8	45.4	34.1	12.8	13.2	0.6	-2.3	47.0	356.5	331.6	1,489	2,499	104%	32	19	26%	7
1999	287.0	297.0	193.2	133.3	137.8	115.8	48.2	13.3	5.8	51.6	293.2	249.7	1,967	3,300	137%	53	113	154%	43
2000	118.7	130.5	140.7	101.9	104.9	69.4	12.8	4.3	9.2	85.2	85.8	165.4	1,287	2,159	90%	17	44	60%	22
2001	155.0	80.0	101.4	97.0	96.3	25.4	7.0	32.4	16.0	61.8	247.1	255.4	947	1,589	66%	3	93	127%	38
2002	308.1	180.7	119.0	168.1	75.3	39.8	13.9	1.6	5.4	3.1	245.5	209.0	1,476	2,477	103%	30	35	48%	18
2003	346.1	89.1	294.3	153.9	34.5	12.4	6.5	-2.9	3.2	312.8	132.2	233.6	1,395	2,340	97%	26	12	16%	2
2004	245.3	132.3	138.3	57.7	22.8	14.6	4.2	9.5	38.1	89.2	189.4	220.9	1,341	2,251	93%	21	87	118%	34
2005	313.5	65.3	100.3	191.2	92.2	22.5	21.1	2.3	8.8	108.2	167.0	224.2	1,317	2,209	92%	20	54	74%	26
2006	417.2	159.8	135.8	112.6	68.6	30.0	5.1	-2.0	4.9	15.9	471.4	302.5	1,431	2,401	100%	29	13	18%	3
2007	318.3	151.4	329.3	122.1	72.7	32.7	29.2	7.4	11.6	178.2	203.0	282.0	1,865	3,128	130%	50	81	110%	33
2008	176.4	94.6	126.4	64.8	142.4	54.3	15.3	20.3	11.7	53.1	193.7	62.2	1,369	2,298	95%	24	79	108%	32
Average 1955-2007	233.1	176.0	161.7	128.2	85.9	42.3	18.5	8.6	17.4	102.8	216.2	249.6	1,438	2,412			73		
Standard Deviation	104.7	79.2	69.2	43.5	40.9	28.1	15.3	13.5	17.7	77.1	106.8	87.8	288	483			55		
1971-2000 Normal	216.8	190.8	167.5	118.9	84.6	44.9	19.3	8.7	16.0	84.5	220.5	237.9	1,414	2,372			74		
Max (1955-2007)	437.4	379.0	333.3	239.9	191.2	137.2	68.0	84.6	75.0	312.8	476.9	476.1	2,026	3,399		(1974)	255		(1997)
Min (1955-2007)	35.2	63.0	51.2	45.4	22.8	9.2	0.6	-2.9	-2.3	1.3	52.9	76.6	919	1,543		(1977)	4		(1985)