Safe Yield for Jointly Operated Reservoir System and Examination of ENSO Impacts

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Abstract

Determination of safe yield of a water source is a basic aspect of water supply planning. In this report, the safe yield is defined as the maximum constant release from a reservoir that is possible during a selected drought period. The yield depends on drought magnitude and duration controlled by nature and ability to manipulate the releases through man made controls in the form of impoundment structures and regulations. A water supply system with two reservoirs in series and one in parallel in Spotsylvania County– the Hunting Run Reservoir, the Motts Run Reservoir (in series), and the Ni River Reservoir is considered to demonstrate the yield calculations.

When several reservoirs are considered, the critical periods (defined as the period from full storage to empty condition) may not coincide and the system must be analyzed for the binding critical duration. A zero-one linear integer programming formulation is proposed to compute the system yield. The formulation accommodates the various storage and river flow dependent instream flow requirements. It is found that the water treatment plant capacity, instream flow requirements, and flows themselves limit the yield.

Inflows to the reservoir are very important factor in determination of safe yield for any system of reservoirs. Changes in the precipitation hence inflows may cause a significant effect on the operation of reservoir. El Nino and La Nina phenomena, which occur due to changes in the atmospheric condition over the equatorial Pacific region, are found to affect the global climate in different studies. To examine the changes in the precipitation / streamflows due to El Nino and La Nina events on the safe yield, studies are done on the streamflows in the study area and four regions across the world during El Nino and LA Nina events. Lag correlation studies and descriptive analysis of the streamflows in the study region in Northern Virginia fail to show any pattern in the streamflow changes due to El Nino and La Nina events, based on the available data. However, this observation is not conclusive and further research is needed.

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1. Introduction

In hydrology, the extreme events are floods and droughts. Floods are a problem when the peak flows are higher than the magnitudes that can be contained by natural or constructed infrastructure. The main components of concern for flood flow analysis are the magnitude and the frequency. Key components of drought are not only the magnitude (lack of water) and frequency (how often a particular severe drought will occur), but also the duration (the length of time this lack of water lasts). Preparing for a drought in the form of building reservoirs and other types of arrangements (for example buying water from other county) can be very costly. However, not preparing for drought can be even costlier. Droughts are typically associated with the following: lack of rain, dry streambeds, fallen groundwater table, withered crops, low supply of certain commodities and water restrictions. Obviously, lack of water affects agriculture; for water-intensive industries, a shortage in the water supply could force a temporary shutdown of the industry, harming the local economy. Low flows present problems for self-assimilative capacity of streams, impede power generating potential of hydro units, and impair navigation of boats. Aquatic life can be damaged during low flows, which may or may not have significant economic impacts, but definitely can present environmental problems. Finally, recreational uses of streams and lakes hampered by low flows have economic impacts and are problematic in public relations.

The instream flow requirements pose special difficulties in satisfying regular demands. For instance, suppose the federal government has regulated a minimum flow downstream of a reservoir that must always be met. As a drought worsens and the flow in the river drops below this minimum flow, the requirement will prevent withdrawal of water from the river and therefore, hastens the depletion of the reservoir. However, if the minimum flow is not required but just guidance, then the uses can be prioritized against the available water supply. The authority may decide that providing potable water to its residents should have higher priority over potential environmental problems resulting from low flows harming aquatic life or the dilution capabilities of sewage treatment effluent. It would also have to measure these impacts against the loss of potential shipping revenues if the flow becomes so low that it prohibits navigation in the river.

One of the supply-side variables is where the locality would obtain water if its water supply were emptied. If the locality holds an agreement with a neighboring jurisdiction, it might be possible to purchase water. If the neighboring area is also suffering through a drought, interbasin transfer along with stringent conservation measures will have to be initiated.

Safe yield of the reservoir or a system of reservoirs depends on the inflows to the reservoir. It is very important to study the factors which affect inflows and hence the safe yield of any system. In the past studies, El Nino and La Nina events were found to be causing a significant change in the precipitation of a region. In this report, studies were done on the precipitation/ stream flows of the five regions across the world including the Northern Virginia to identify a change in the precipitation/ streamflow pattern due to El Nino and La Nina events.

1.1 Organization of the Report

The report is organized as follows. Chapter 2 presents the methodology for safe yield calculation. Chapter 3 contains the details of the system considered along with a system schematic and an exhaustive set of data tables. Chapter 4 details the zero-one mathematical programming formulation for computing the yield. This general formulation contains the storage, water treatment, pumpage capacity and storage – river flow dependent maximum instream flow and continuity constraints. The results are reported in Chapter 5. It also contains a summary of key contributions of this research. Chapter 6 describes the El Nino – Southern Oscillation (ENSO) phenomenon in detail. El Nino/ La Nina events are found to be affecting the streamflows across the world in the past studies. Streamflows/ precipitation dataset for five regions across the world are analyzed to identify a pattern with El Nino/ La Nina events. Chapter 7 describes the analyses done and results obtained from the analyses. Chapter 8 gives a detailed discussion of the result obtained from the analyses. Chapter 9 summarizes the work done and the scope of further studies.

2. Safe Yield

Determining the safe yield of an existing water supply is a basic aspect of water supply planning. Where water is withdrawn from a river directly without any storage, the withdrawal is constrained by the worst drought flow in the river. There is no room for operational adjustments other than implementing conservation measures. Where there is a storage reservoir, yields higher than the flow in the source stream can be maintained for a period of time by releasing the water in storage. The determination of safe yield in this situation requires elaborate computation. Determination of safe yield traditionally has been based on the mass curve and a constant draft method to compute the maximum acceptable withdrawal rate as dictated by a historical drought sequence. It should be noted that this definition implies inclusion of both drought severity (magnitude of shortage) and critical duration (sequencing of flows). The *critical duration* is defined as the period from full reservoir to empty reservoir. Utilizing these concepts the yield is given by

Yield = (Reservoir Capacity + Cumulative Inflow over the Critical Drought Period) /Critical Drought Period …………..2.1

When a town depends on river flow directly without a storage reservoir, it has little control option. In such a situation, the reliability is measured in terms of the 30-year 1-day flow (or a suitable threshold flow value) and the demand. However, with a storage reservoir a set of control options are possible. The Virginia State Water Control Board [SWBC] (1985) [also see McMahon and Mein(1986) for a review] has provided planning level yield estimates for municipal water supply systems. The method involves the following steps. First, a historically worst drought sequence is selected. Second, a constant draft (withdrawal rate) is assumed. Third, assuming the reservoir to be full at the first period, the continuity (volume balance) equation is applied using the constant draft. Fourth, at the end of the drought sequence the storage is checked for its emptiness; if it is not empty, the draft rate in step2 is modified and the steps are repeated. The resulting constant draft rate is called the yield. This type of planning level method provides an assessment of the overall water supply potential of the system but does not give an acceptable control rule for day to day operation; no detailed system performance measures are available; and no guidance towards conservation measures is available. Therefore, each reservoir has a safe yield for a certain characteristic drought – the amount of water that the reservoir could safely be relied upon to provide during a certain characteristic drought. This safe yield would vary according to the magnitude and duration of the drought – naturally, for a more extreme or longer duration drought, the safe yield of the reservoir will be less. In terms of recurrence periods, the safe yield for the 100-year drought will be greater than the safe yield for the 500-year drought. Likewise, the assumptions made in determining the inflow sequence will also affect the safe yield. More conservative assumptions will reduce the safe yield. Another noteworthy point is that the yield computation does not consider the demands. It answers the question what is the greatest constant demand that can be satisfied while receiving inflows as specified for an initial storage of full reservoir.

2.1 Mass curve Method and identification of Critical drought sequence

A method to calculate safe yield and identification of critical drought sequence is the analytical mass curve method (Loucks, et al., 1981). The basic variables involved are inflow (I_i) and demand (y_i) for each period i. Demand (y_i) in this method is synonymous with the yield in the sense that the largest constant demand that can be satisfied is the yield itself. Hence, for yield calculations we set $y_i = y$ (constant yield). The deficit for period i given by $dd_i = y_i - I_i$.

The deficit is positive when the demand y_i (or y) exceeds the inflow volume, which will usually be the case in the drought situation. The cumulative deficit (draw-down) k_i, or volume between the current reservoir level and the full pool level is the sum of the cumulative deficit up to and including period i-1 plus the current deficit dd_i. Thus, when the reservoir is full, k_i is equal to zero; when it is empty, it is equal to the capacity of the reservoir. The typical assumption is that the reservoir is full at the beginning of the analysis period so that k_0 is equal to zero.

The negative deficit indicates that the inflow is greater than the demand. When the cumulative deficit turns negative, the reservoir has been filled to the capacity and the physical deficit is zero. This capacity limit is imposed by defining a new variable Adjusted k_i, given by

Adjusted k_i $= k_i$ if $k_i > 0$

and $= 0$ if $k_i \leq 0$ ……………………….2.2

It is noted that Adjusted k_i calculates the various partial sums of deficits and typically the largest deficit corresponds to the storage. Therefore if one starts with an Adjusted k_{i1} of zero for some i = i1 and when it reaches the storage capacity for the first time at i = i2, the critical period is identified as (i2 – i1). The steps are demonstrated for an inflow sequence for the Hunting Run Reservoir in the Rappahanock River basin shown in Table 2.1. In Table 2.1, the constant demand value is adjusted until the maximum Adjusted k_i value equals the capacity of the reservoir and the corresponding demand equals the yield. The goal-seek function in Microsoft Excel can be easily used to obtain the result. For a storage capacity of 2194.16 mg, the critical period begins in i1 = 5 and end in i2 = 19 for a critical duration of 14 periods. Applying equation 2.1 we have yield = (2194.16 + 129.84)/14 = 166 mg that agrees with the yield shown in Table 2.1.

Critical drought sequence is identified as the period during which the reservoir empties itself fully from being full at the beginning at the starting of the period.

Table 2.1 Tabular method to calculate safe yield

Period i	Duration (days)	Inflow (Mgal)	Greatest Constant Demand (Yield) (Mgal)	Yield - Withdrawal (Mgal)	Ki-1 (Mgal)	Ki (Mgal)	Adjusted Ki (Mgal)
1	30	600.00	166	-434.00	0.00	-434.00	0.00
2	60	600.00	166	-434.00	0.00	-434.00	0.00
3	90	600.00	166	-434.00	0.00	-434.00	0.00
4	120	600.00	166	-434.00	0.00	-434.00	0.00
5	150	600.00	166	-434.00	0.00	-434.00	0.00
6	180	129.84	166	36.16	0.00	36.16	36.16
7	210	0.00	166	166.00	36.16	202.16	202.16
8	240	0.00	166	166.00	202.16	368.16	368.16
9	270	0.00	166	166.00	368.16	534.16	534.16
10	300	0.00	166	166.00	534.16	700.16	700.16
11	330	0.00	166	166.00	700.16	866.16	866.16
12	360	0.00	166	166.00	866.16	1032.16	1032.16
13	390	0.00	166	166.00	1032.16	1198.16	1198.16
14	420	0.00	166	166.00	1198.16	1364.16	1364.16
15	450	0.00	166	166.00	1364.16	1530.16	1530.16
16	480	0.00	166	166.00	1530.16	1696.16	1696.16
17	510	0.00	166	166.00	1696.16	1862.16	1862.16
18	540	0.00	166	166.00	1862.16	2028.16	2028.16
19	570	0.00	166	166.00	2028.16	2194.16	2194.16
20	600	257.84	166	-91.84	2194.16	2102.31	2102.31
21	630	600.00	166	-434.00	2102.31	1668.31	1668.31
22	660	600.00	166	-434.00	1668.31	1234.31	1234.31
23	690	600.00	166	-434.00	1234.31	800.31	800.31
24	720	600.00	166	-434.00	800.31	366.31	366.31

3. System Description and Data Collected

3.1 System Description

The system considered is comprised of three reservoirs in Spotsylvania County, Virginia, a fast-growing county about fifty miles south of Washington, D.C. The three reservoirs of interest are: Hunting Run Reservoir, Motts Run Reservoir, and Ni River Reservoir. A schematic of the system is given in Figure 3.1. The Hunting Run reservoir is currently under construction, and the other two are already in use. This system of reservoirs provides drinking water to Spotsylvania County. The Hunting Run and Motts Run are offline reservoirs which receive pumped in water from the Rapidan and the Rappahanock River respectively, while the Ni River Reservoir is directly fed by the Ni River.

3.1.1 Hunting Run Reservoir

As mentioned above, the Hunting Run Reservoir is currently under construction. It is being built to complement the other reservoirs in providing drinking water for Spotsylvania County. The design safe yield of the reservoir, as calculated by consulting engineers Hayes, Seay, Mattern, & Mattern, is 8.0 million gallons per day (mgd). The reservoir is located on a tributary, Hunting Run, to the Rapidan River just above its confluence with the Rappahanock River. It has a capacity of 2196 mg.

The reservoir is designed so that inflows will consist of natural runoff from the Hunting Run, as well as water pumped from the Rapidan River when the river flow is above the specified minimum instream flows. The instream flow requirements are based on the flow in the river as well as the storage in the reservoir. The Hunting Run watershed (4,620 acres) is very small compared with the Rapidan River watershed at the pumping site (686 square miles, or approximately 439,000 acres). As a result, for the analysis, only the water available for pumping was of interest. As seen in Figure 3.1, the reservoir is on the west end of the county. Its watershed is very rural, with not much development. The pumping site on the Rapidan is approximately halfway between USGS gauging sites at Culpeper (on the Rapidan River) and Fredericksburg (on the Rappahanock). Since the pumping site is upstream of the confluence of the Rapidan and Rappahanock, for the analysis, the Culpeper site was used. The drainage area at Culpeper is 472 square miles which results in a drainage area ratio of 1.486 (Final Environmental Impact Report Submitted to the County of Spotsylvania by Hayes, Seay, Mattern and Mattern, Inc (HSMM, 1994), in March 1994) for the adjustment of flows measured at the Hunting Run pumping site. The maximum pumpage rate is limited to 24 mgd. The instream flow requirements are shown in Table 3.1.

Even though 1931 to be the worst drought on record, the yield analysis procedure identifies May 1965 – November 1966 to be the most stringent critical period for the Rapidan River inflows. The same critical period applies to the Motts Run reservoir as well; for the Ni River reservoir the critical period starts in June 1980 and ends in Nov 1981. The flows are shown in Table 3.2 for the Rapidan River. Rapidan River streamflows are attached as Appendix B.

3.1.2 Motts Run Reservoir

Motts Run Reservoir provides drinking water Spotsylvania County. The safe yield of the reservoir is 3.4 mgd. The reservoir is located on a tributary (Motts Run) to the Rappahanock River downstream of its confluence with the Rappahanock River, and just upstream from the City of Fredericksburg. It has a capacity of 1205 mg. Similar to Hunting Run Reservoir; the reservoir is designed so that inflows will consist of natural runoff from Motts Run, as well as water pumped from the Rappahanock River when the river is above certain minimum flows. The instream flow limits are given in Table 3.4. Tables 3.5 and 3.6 provide the inflows adjusted from the Fredericksburg gage with a multiplying factor of 0.98 (Final Environmental Impact Report Submitted to the County of Spotsylvania by Hayes, Seay, Mattern and Mattern, Inc (HSMM, 1994), in March 1994). Table 3.5 represents Motts Run critical period.

The difference in the watershed areas between Motts Run and the Rappahanock is even greater than that for Hunting Run. The Motts Run watershed consists of 6,834 acres while the Rappahanock River watershed consists of 1,570 square miles (approximately 1,005,000 acres). Again, because of this magnitude of difference, for the analysis, only the water available for pumping was of interest. As can be seen in Figure 3.1, the reservoir is to the east, and downstream, of Hunting Run Reservoir. Its watershed is approximately 50% rural, 25% commercial, and 25% residential. The pumping site on the Rappahanock is closest to the USGS gauging site at Fredericksburg. Since the pumping site is so close to the gauging site at Fredericksburg, a multiplying factor of 0.98 is used for flow adjustment between the two sites. Raappahannock River streamflows are attached as Appendix A.

3.1.3 Ni River Reservoir

The Ni River Reservoir also provides drinking water Spotsylvania County, with a safe yield of 4.0 mgd. It has a capacity of 750 mg. And a separate treatment plant with a capacity of 6 mgd (Final Environmental Impact Report Submitted to the County of Spotsylvania by Hayes, Seay, Mattern and Mattern, Inc (HSMM, 1994), in March 1994). It is somewhat different in nature than the other two reservoirs. For one, it is in a different basin, the Mattaponi River basin. The reservoir is located on the Ni River, and the only inflow to the reservoir is the flow from the river (no pumping).
As seen in Figure 3.1, the reservoir is to south of the other two reservoirs. Its watershed is approximately 60% rural, 15% residential, and 25% parkland (Fredericksburg-Spotsylvania National Historic Park). There are no gauges on the Ni River. There is a gauge somewhat close to the reservoir, on the Po River (Po River streamflows are attached as Appendix B). The Ni River reservoir has a drainage area of 25 sq. miles and the gage on the Po River has a drainage area of 77.4 square miles. The monthly average flows at the gage are taken and multiplied by a factor of (25/77.4) (Final Environmental Impact Report Submitted to the County of Spotsylvania by Hayes, Seay, Mattern and Mattern, Inc (HSMM, 1994), in March 1994), to obtain the inflows to the Ni river reservoir. However, the period of record for this gauging station is only from 1962, which misses some of the worst droughts of the 20th century. As a result, the usefulness of this data is somewhat limited. The critical drought period for the Ni River is from June 1980 through December 1981. Table 3.6 represents the Ni River critical period. Tables 3.7 and 3.8 show the inflows corresponding to the critical periods for the Motts Run/ Hunting

Run reservoirs and the Ni River reservoir. Table 3.9 summarizes the period of data availability and Table 3.10 contains the average monthly flows.

Table 3.1 Instream Conditions at Hunting Run Reservoir for Withdrawal from Rapidan River

Month	Emergency Volumes at Hunting Run (MG)	Provision. Storage* at Hunting Run(MG)	Rules	Instream Flow (% of MAF)	Instream Flow at Rapidan (cfs)	MG Per Month (cfs*days* 0.6463)
Jan.	990		If Storage is greater than 990 million gallons	40	306.00	6130.54
			If Storage is less than 990 million gallons	20	153.00	3065.27
Feb.	1100		If Storage is greater than 1100 million gallons	40	306.00	5537.26
			If Storage is less than 1100 million gallons	20	153.00	2768.63
Mar.	1320	2002 (91%)	If Storage is greater than 1320 million gallons but less than 2002 million gallons	60	459.00	9195.80
			If Storage is less than 1320 million gallons	40	306.00	6130.54
April	1540	2068 (94%)	If Storage is greater than 1540 million gallons but less than 2068 million gallons	60	459.00	8899.17
			If Storage is less than 1540 million gallons	40	306.00	5932.78
May	1760	2134 (97%)	If Storage is greater than 1760 million gallons but less than 2134 million gallons	60	459.00	9195.80
			If Storage is less than 1760 million gallons	40	306.00	6130.54
June	1540		If Storage is greater than 1540 million gallons	60	459.00	8899.17
			If Storage is less than 1540 million gallons	20	153.00	2966.39

July	1320		If Storage is greater than 1320 million gallons	40	306.00	6130.54
			If Storage is less than 1320 million gallons	20	153.00	3065.27
Aug.	1100		If Storage is greater than 1100 million gallons	40	306.00	6130.54
			If Storage is less than 1100 million gallons	20	153.00	3065.27
Sept.	990		If Storage is greater than 990 million gallons	40	306.00	5932.78
			If Storage is less than 990 million gallons	20	153.00	2966.39
Oct.	990		If Storage is greater than 990 million gallons	40	306.00	6130.54
			If Storage is less than 990 million gallons	20	153.00	3065.27
Nov.	880		If Storage is greater than 880 million gallons	40	306.00	5932.78
			If Storage is less than 880 million gallons	20	153.00	2966.39
Dec.	880		If Storage is greater than 880 million gallons	40	306.00	6130.54
			If Storage is less than 880 million gallons	20	153.00	3065.27

* If storage > provisional storage, then instream requirement =764 cfs (Rapidan Mean Annual Flow)

Table 3.2 River Inflows Available for Hunting Run Reservoir for May 65-Nov 66

Month-Year	Days	Annual Monthly Rapidan Flows (cfs)	Drainage Area corrected flow = 1.486*flow (cfs)	Inflow Volume = Corrected flow*days* 0.6463 (MG per month)
May-65	31	341	506.7	10152.7
Jun-65	30	160	237.8	4610.0
Jul-65	31	104	154.5	3096.4
Aug-65	31	73	108.5	2173.4
Sep-65	30	64.3	95.5	1852.7
Oct-65	31	133	197.6	3959.8
Nov-65	30	85.2	126.6	2454.9
Dec-65	31	70.5	104.8	2099.0
Jan-66	31	93.6	139.1	2786.8
Feb-66	28	759	1127.9	20411.0
Mar-66	31	584	867.8	17387.6
Apr-66	30	375	557.3	10804.8
May-66	31	693	1029.8	20632.9
Jun-66	30	195	289.8	5618.5
Jul-66	31	70.7	105.1	2105.0
Aug-66	31	34.9	51.9	1039.1
Sep-66	30	511	759.3	14723.3
Oct-66	31	536	796.5	15958.5
Nov-66	30	346	514.2	9969.2

Table 3.3 River Inflows Available for Hunting Run Reservoir for Jun 80-Dec81

Month-Year	Days	Annual Monthly Rapidan Flows (cfs)	Drainage Area corrected flow = 1.486*flow (cfs)	Inflow Volume = Corrected flow*days* 0.6463 (MG per month)
Jun-80	30	268	398.2	7721.8
Jul-80	31	196	291.3	5835.6
Aug-80	31	170	252.6	5061.5
Sep-80	30	83.4	123.9	2403.0
Oct-80	31	99.7	148.2	2968.4
Nov-80	30	161	239.2	4638.9
Dec-80	31	144	214.0	4287.3
Jan-81	31	111	164.9	3304.8
Feb-81	28	620	921.3	16673.0
Mar-81	31	248	368.5	7383.8
Apr-81	30	210	312.1	6050.7
May-81	31	293	435.4	8723.6
Jun-81	30	346	514.2	9969.2
Jul-81	31	389	578.1	11581.8
Aug-81	31	108	160.5	3215.5
Sep-81	30	145	215.5	4177.9
Oct-81	31	192	285.3	5716.5
Nov-81	30	164	243.7	4725.3
Dec-81	31	227	337.3	6758.5

Table 3.4 Instream Conditions at Motts Run Reservoir for Withdrawal from Rappahannock River

Month	Emergency Volumes at Hunting Run (MG)	Provisional Volume at Motts Run (MG)	Rules	Instream Flow (% MAF)	Instream Flow at Rappah .(cfs)	MG Per Month (cfs*days* 0.6463)
Jan.	543		If Storage is greater than 543 million gallons	40	641.00	12842.07
			If Storage is less than 543 million gallons	20	321.00	6431.05
Feb.	602		If Storage is greater than 602 million gallons	40	641.00	11599.29
			If Storage is less than 602 million gallons	20	321.00	5808.69
Mar.	723	1097 (91% full)	If Storage is greater than 723 million gallons but less than 1097 million gallons	60	962.00	19273.12
			If Storage is less than 723 million gallons	40	641.00	12842.07
April	843	1133 (94% full)	If Storage is greater than 843 million gallons but less than 1133 million gallons	60	962.00	18651.41
			If Storage is less than 843 million gallons	40	641.00	12427.81
May	973	1169 (97% full)	If Storage is greater than 973 million gallons but less than 1169 million gallons	60	962.00	19273.12
			If Storage is less than 973 million gallons	40	641.00	12842.07
June	843		If Storage is greater than 843 million gallons	60	962.00	18651.41
			If Storage is less than 843 million gallons	20	321.00	6223.60
July	723		If Storage is greater than 723 million gallons	40	641.00	12842.07

			If Storage is less than 723 million gallons	20	321.00	6431.05
Aug.	602		If Storage is greater than 602 million gallons	40	641.00	12842.07
			If Storage is less than 602 million gallons	20	321.00	6431.05
Sept.	542		If Storage is greater than 542 million gallons	40	641.00	12427.81
			If Storage is less than 542 million gallons	20	321.00	6223.60
Oct.	542		If Storage is greater than 542 million gallons	40	641.00	12842.07
			If Storage is less than 542 million gallons	20	321.00	6431.05
Nov.	482		If Storage is greater than 482 million gallons	40	641.00	12427.81
			If Storage is less than 482 million gallons	20	321.00	6223.60
Dec.	482		If Storage is greater than 482 million gallons	40	641.00	12842.07
			If Storage is less than 482 million gallons	20	321.00	6431.05

* If storage > provisional storage, then instream requirement =1630 cfs [32656.12 MG per month] (Rappahannock Mean Annual Flow)

Table 3.5 River Inflows Available for Motts Run Reservoir for May 65 – Nov 66

Month-Year	Days	Annual Monthly Rappahannock Flows (cfs)	Drainage Area corrected flow = 0.98*flow (cfs)	Inflow Volume = Corrected flow*days* 0.6463 (MG per month)
May-65	31	880	862.4	17278.9
Jun-65	30	405	396.9	7695.7
Jul-65	31	261	255.8	5124.8
Aug-65	31	192	188.2	3769.9
Sep-65	30	156	152.9	2964.3
Oct-65	31	277	271.5	5438.9
Nov-65	30	204	199.9	3876.4
Dec-65	31	205	200.9	4025.2
Jan-66	31	268	262.6	5262.2
Feb-66	28	2461	2411.8	43645.7
Mar-66	31	1611	1578.8	31632.2
Apr-66	30	1168	1144.6	22194.0
May-66	31	2049	2008.0	40232.3
Jun-66	30	508	497.8	9652.9
Jul-66	31	141	138.2	2768.6
Aug-66	31	76.4	74.9	1500.1
Sep-66	30	1965	1925.7	37338.4
Oct-66	31	1835	1798.3	36030.4
Nov-66	30	840	823.2	15961.4

Average monthly Rappahannock River flows were obtained from the USGS gage # 01668000 Rappahannock River near Fredericksburg VA, from the USGS website.

Table 3.6 River Inflows Available for Motts Run Reservoir Jun 80 – Dec 81

Month-Year	Days	Annual Monthly Rappahannock Flows (cfs)	Drainage Area corrected flow = 0.98*flow (cfs)	Inflow Volume = Corrected flow*days* 0.6463 (MG per month)
Jun-80	30	930	911.4	17671.6
Jul-80	31	526	515.5	10328.1
Aug-80	31	508	497.8	9974.6
Sep-80	30	187	183.3	3553.3
Oct-80	31	200	196.0	3927.0
Nov-80	30	393	385.1	7467.7
Dec-80	31	364	356.7	7147.2
Jan-81	31	297	291.1	5831.6
Feb-81	28	1751	1716.0	31053.9
Mar-81	31	620	607.6	12173.8
Apr-81	30	587	575.3	11154.0
May-81	31	809	792.8	15884.8
Jun-81	30	744	729.1	14137.3
Jul-81	31	608	595.8	11938.1
Aug-81	31	362	354.8	7107.9
Sep-81	30	373	365.5	7087.6
Oct-81	31	421	412.6	8266.4
Nov-81	30	387	379.3	7353.7
Dec-81	31	622	609.6	12213.0

Table 3.7 River Inflows to the Ni River Reservoir (Obtained by applying a Drainage Area Factor of (25/77.4) to the Po River gage Data) May 65-Nov 66

Month-Year	Days	Monthly Averaged flows in Po River (cfs per month)	Monthly Inflows to Ni River Reservoir (After Applying Drainage Area Factor of 25/77.4 to Po River gage Data) (cfs per month)	Monthly Inflows to Ni River Reservoir (cfs*days*0.6463) (MG per month)
May-65	31	39.4	12.7	255.0
Jun-65	30	23.9	7.7	149.7
Jul-65	31	22.6	7.3	146.3
Aug-65	31	18.1	5.8	117.1
Sep-65	30	9.25	3.0	57.9
Oct-65	31	15	4.8	97.1
Nov-65	30	9.35	3.0	58.6
Dec-65	31	11.1	3.6	71.8
Jan-66	31	26.8	8.7	173.4
Feb-66	28	133	43.0	777.4
Mar-66	31	77	24.9	498.3
Apr-66	30	67	21.6	419.6
May-66	31	70.3	22.7	454.9
Jun-66	30	13	4.2	81.4
Jul-66	31	6.94	2.2	44.9
Aug-66	31	0.77	0.2	5.0
Sep-66	30	65.7	21.2	411.5
Oct-66	31	79.7	25.7	515.8
Nov-66	30	25.1	8.1	157.2

Table 3.8 River Inflows to the Ni River Reservoir (Obtained by applying a Drainage Area Factor of (25/77.4) to the Po River gage Data) for Jun 80 – Dec 81

Month-Year	Days	Monthly Averaged flows in Po River (cfs per month)	Monthly Inflows to Ni River Reservoir (After Applying Drainage Area Factor of 25/77.4 to Po River gage Data) (cfs per month)	Monthly Inflows to Ni River Reservoir (cfs*days*0.6463) (MG per month)
Jun-80	30	19.3	6.2	120.9
Jul-80	31	7.15	2.3	46.3
Aug-80	31	2.14	0.7	13.8
Sep-80	30	0.94	0.3	5.9
Oct-80	31	4.52	1.5	29.3
Nov-80	30	15.4	5.0	96.4
Dec-80	31	12.2	3.9	79.0
Jan-81	31	10.4	3.4	67.3
Feb-81	28	59.5	19.2	347.8
Mar-81	31	25.2	8.1	163.1
Apr-81	30	27.1	8.8	169.7
May-81	31	52.9	17.1	342.3
Jun-81	30	6.97	2.3	43.7
Jul-81	31	9.1	2.9	58.9
Aug-81	31	3.28	1.1	21.2
Sep-81	30	1.37	0.4	8.6
Oct-81	31	6.86	2.2	44.4
Nov-81	30	3.85	1.2	24.1
Dec-81	31	35.2	11.4	227.8

Table 3.9 USGS Gauging Stations for Project

Site	River	Period of record	Drainage area (square miles)
Fredericksburg	Rappahanock	1907- present	1,596
Culpeper	Rapidan	1930- present	472
Spotsylvania	Po	1962- present	77

Table 3.10 Mean monthly flows, Culpeper and Fredericksburg

Month	Rapidan	Rappahannock	Po
	Culpeper	Fredericksburg	Spotsylvania
	1667500	1668000	1673800
	Cfs*	Cfs*	Cfs*
January	666	2197	115
February	735	2489	133
March	845	2698	154
April	773	2480	113
May	573	1891	74.7
June	482	1414	52.1
July	300	907	29
August	329	1006	24.1
September	364	948	25.5
October	421	1148	42
November	463	1308	62.7
December	549	1661	83

1Mgd = 0.646317cfs

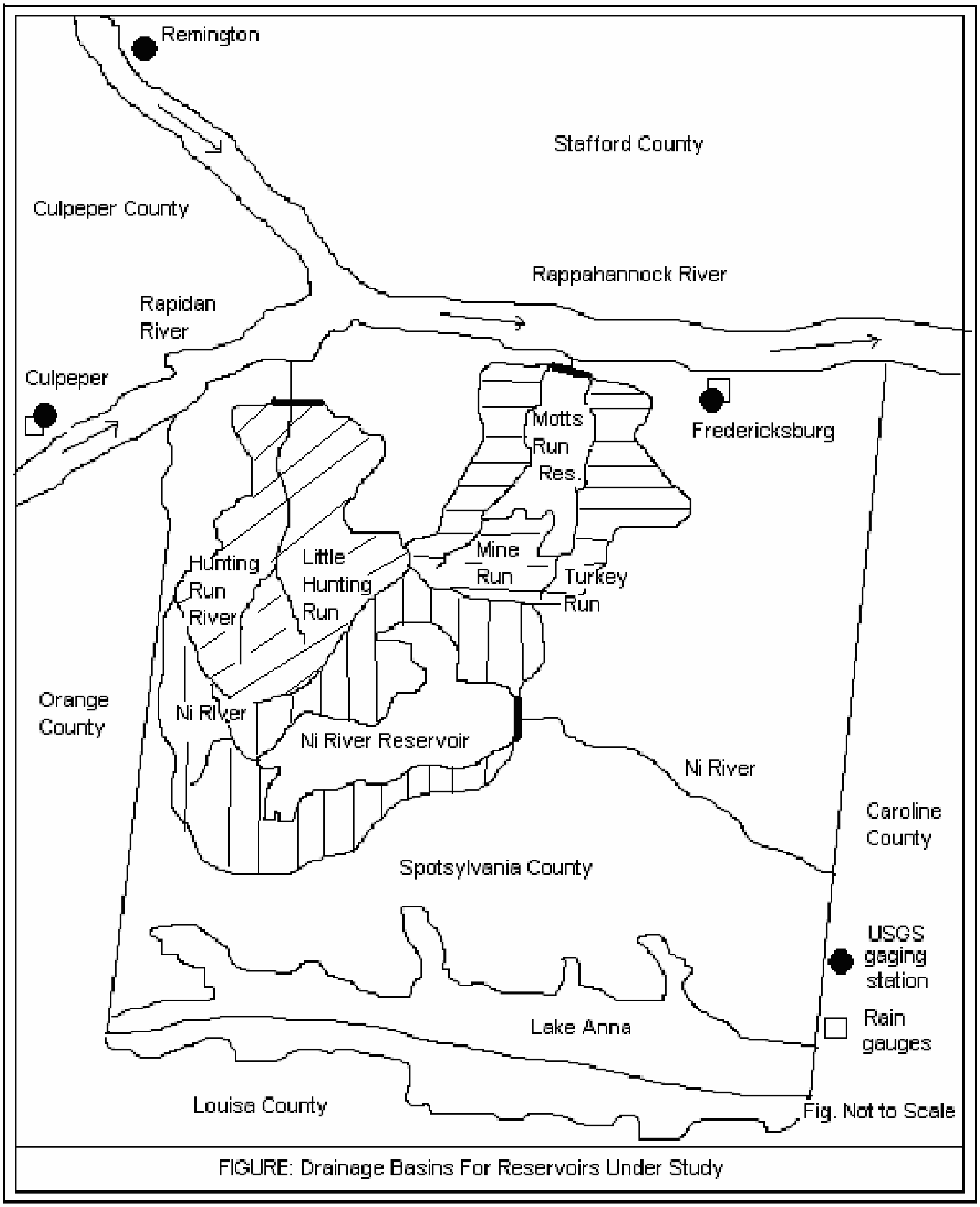


Figure 3.1 System schematic

4. Yield Computation by Mathematical Programming

4.1 Introduction

In this chapter a mathematical programming formulation for calculating the yield is presented. The formulation considers the Hunting Run and Motts Run reservoirs in series and the Ni reservoir in parallel. The data presented in chapter 3 on critical period inflows, instream flow requirements, capacity limits on the reservoirs and water treatment plant are used. The current capacity limit of 12 mgd at the Motts Run reservoir and future capacity of 24 mgd are considered. The integer mathematical programming problem is solved with an enhanced version of the LINGO solver (Lindo Systems, 2000). Detailed explanation about the use of LINGO software is given in Appendix D.

4.2 Mathematical Formulation

1. *Continuity constraint*: This constraint relates the storage of the i^{th} reservoir $S_i(t)$ at the beginning of period t to the storage at the beginning of the next period (t+1) $S_i(t+1)$ with the pumped inflow, $I_i(t)$, the release, $R_i(t)$, and spillage, $spill_i(t)$ by

$$S_i(t+1) = S_i(t) + I_i(t) - R_i(t) - spill_i(t)$$

2. *Reservoir capacity constraints*: These constraints limit the storage in the reservoir at any period to be less than the capacity of the reservoir, Cap_i given by

$$S_i(t) \leq Cap_i$$

3. *Water Treatment Plant Capacity constraints:* These constraints limit the release from the reservoir at any period to be less than the water treatment plant capacity, WT_i given by

$$R_i(t) \leq WT_i$$

4. *Yield constraints:* Yield is the maximum amount of water that can be released from the reservoir under the most stringent conditions (critical period)

$$Yield = \max[\min\{R(t)\}]$$

which is formulated as the objective function, *Maximize* Yield, Y such that $Y \leq R(t)$ and R(t) is the sum of all releases, $R_i(t)$.

5. *Instream requirements:* These requirements ensure that the various minimum instream requirement specified by the regulatory agencies are followed. These requirements specify the maximum quantity of flow that can be pumped into the reservoir, $I_i(t)$ given by

$$I_i(t) \leq \text{Minimum}[\text{maximum}\{0, RivFlow_i(t) - ISF_i(t)\}, \text{Pumpage rate}]$$

in which: $RivFlow_i(t)$ = river flow volume to reservoir i during time t, $ISF_i(t)$ = instream flow limit for reservoir i for period t. The instream flow demands vary from month to month based on recreational, and fish and wild life needs. The ISF values also depend on the available storage $S_i(t)$ in the reservoir as shown in Tables 3.1 and 3.4. These requirements are of the form that the instream flow is ISF1 when storage is less than SL1; ISF2 when storage is between SL1 and SL2; and ISF3 when storage S(t) is greater than SL2. These requirements are modeled by introducing the binary variables δ_2, δ_3, δ_4 and the storage variables S1, S2, and S3 for the three ranges as

$$S1(t) \leq SL1$$

$$S1(t) \geq (SL1)\delta_{2t}$$

$$S2(t) \leq (SL2\text{-}SL1)\delta_{2t}$$

$$S2(t) \geq (SL2\text{-}SL1)\delta_{3t}$$

$$S3(t) \leq (Cap - SL2)\delta_{3t}$$

and $$S(t) = S1(t) + S2(t) + S3(t)$$

and $$ISF(t) = ISF1 + (ISF2\text{-}ISF1)\delta_{2t} + (ISF3\text{-}ISF2)\delta_{3t}$$

When $S(t)$ is in the second range indicated by $\delta_{2t} = 1$, we have $S1 = SL1$ and $S2$ is less than or equal to $(SL2 - SL1)$ and $S2$ lies between $SL1$ and $SL2$ as desired. When $\delta_{3t} = 1$, we have $S2 = SL2 - SL1$ and $S1 = SL1$ and therefore $S(t)$ is between $SL2$ and Cap. We may also require that whenever the $spill_i(t)$ is positive, the storage at the end of the period t, $S_i(t+1)$ must equal the capacity by

$$Spill_i(t) \leq M\delta_{st}$$

and $$S(t+1) \geq Cap\ \delta_{st}$$

in which: δ_{st} = 0-1 integer. Whenever $\delta_{st} = 1$,
by $S(t+1) = S1(t+1) + S2(t+1) + S3(t+1) \leq Cap$ and $S(t+1) \geq Cap\ \delta_{st}$
we have $S(t+1) = Cap$. When $\delta_{st} = 0$, $S(t+1) \geq Cap\ \delta_{st}$ results in nonnegativity and all constraints are properly considered.

To ensure the river flow, RivFlow(t) remains greater than the instream flow requirement, ISF(t), before pumping we formulate the following constraints. The variable INS(t) represents the quantity of available water in excess of the instream flow, ISF(t) that remains in the river and allows for pumping.
If instream flow requirement ISF(t) is less than the river flow, RivFlow(t), the maximum quantity available for pumpage INS(t) must equal the quantity in excess of the river flow expressed as RivFlow(t) –ISF(t).

$$INS(t) \leq RivFlow(t) + M\delta_{4t}$$

$$INS(t) \geq [RivFlow(t) - ISF(t)] - M\delta_{4t}$$

$$INS(t) \leq [RivFlow(t) - ISF(t)] + M\delta_{4t}$$

in which M is a very large number. When the binary variable $\delta_{4t} = 1$, the above constraints are nonbonding due to the large value of M. When $\delta_{4t} = 0$, the above constraints are binding and together set $INS(t) = [RivFlow(t) - ISF(t)]$ as desired.
When $\delta_{4t} = 0$, $INS(t) \leq RivFlow(t)$; When $\delta_{4t} = 1$, we enforce $INS(t) > RivFlow(t)$ as follows. In addition, if instream flow requirement ISF(t) is greater than the river flow, RivFlow(t), the maximum quantity available for pumpage INS(t) must be zero.

$$ISF(t) \geq RivFlow(t) + \varepsilon - M(1-\delta_{4t})$$

in which ε = small number say, 0.00000001.

$$INS(t) \leq M(1- \delta_{4t})$$

In the above constraints, when $\delta_{4t} = 1$, $ISF(t) \geq RivFlow(t) + \varepsilon$; and $INS(t) \leq 0$. Due to nonnegativity of the variables INS(t) = 0.

6. *Pump-in flow limit:* Therefore the pumped-in flow to the reservoir $I_i(t)$ must satisfy the constraints

$$I_i(t) \leq INS(t)$$

and $$I_i(t) \leq \text{Pumpage rate}$$

The above sets of constraints are formulated for each reservoir and the problem is solved maximizing the Yield, Y such that $Y \leq \sum_{1}^{3} R_i(t)$.

A detailed example of above mentioned optimization program for calculating the safe yield using the LINGO solver is given in Appendix-E.

5. Results and Discussion

The mathematical formulation presented in chapter 4 is solved for four scenarios corresponding to the critical periods of June 1980 – December 1981[Ni River reservoir] and May 1965 – November 1966 [Motts Run and Hunting Run reservoirs] and water treatment plant capacities of 12 mgd and 24 mgd at the Motts Run reservoir (an example of the LINGO output and Input file is given in Appendix E). The resulting safe yield values are shown in Table 5.1. A safe yield of 500.5 mg/month for the Ni critical period and a safe yield of 504 mg/month for the Motts Run and Hunting Run critical periods are obtained showing that the water treatment plant capacity is the limiting factor. A safe yield of 840 mg/month is obtained for the Ni critical period again due to the capacity limitation of 24 mgd for the Motts Run water treatment plant. However, for the Motts Run and Hunting Run critical period a safe yield of only 816.50 mg/month is realized indicating that the inflows are limiting along with the Motts Run water treatment plant capacity.

The complete results are given in Tables 5.2 – 5.13. In all these analyses a monthly time step is used. The water treatment capacities are converted to monthly equivalents from their daily values. In this procedure because February has only 28 days, the capacity limits become binding towards February or when other inflow constraints prevail. When the inflow limits do not apply, we have February limits of 504 mg/month and 840 mg/month become the yield values as given in Table 5.1. Tables 5.2 through 5.7 contain the results for the critical period of the Hunting Run and Motts Run reservoirs of May 1965 – Nov. 1966. Tables 5.2 – 5.4 contain the results for the Motts Run treatment plant capacity of 12 mgd. Tables 5.5 – 5.7 contain the results for the Motts Run treatment plant capacity of 24 mgd. Because May 1965 – Nov.1966 is critical only for the Hunting Run and Motts Run reservoirs, there are spills possible for the Ni reservoir as shown in Table 5.3. Whenever there is spill, the corresponding next period storage is at full capacity. Table 5.4 provides the system yield as 504 mgd corresponding to February 1966.

For the same critical period for the Hunting Run and Motts Run reservoirs with Motts Run water treatment plant capacity of 24 mgd, Tables 5.6 and 5.7 show that the Ni River Reservoir supplies to the capacity of its treatment plant; whereas Hunting Run and Motts Run are so efficiently operated that during January 1966 the Motts Run Reservoir is completely emptied to provide the maximum release equivalent to a yield of 816.5 mg/mo falling short of the maximum yield of 840 mg/mo.

Tables 5.8 – 5.10 contain the results corresponding to the Motts Run treatment plant capacity of 12 mgd. For the Ni River Reservoir critical period of June 1980 – December 1981 a yield of 500.5 mg/mo is obtained. Table 5.8 contains the results for the Hunting Run reservoir. Table 5.9 shows that due to reduced inflows the full potential of the water treatment plant of 6 mgd was not exploited whereas the Hunting Run and the Motts Run reservoirs fully exploit the available treatment plant capacity of 12 mgd. The combination of the releases given in Table 5.9 and 5.10 shows that a yield of only 500.5 mg/mo is possible. Tables 5.11-5.13 contain the results corresponding to the Motts Run treatment plant capacity of 24 mgd. Table 5.11 shows the results for the Hunting Run reservoir for June 1980 – Dec. 1981.

Tables 5.7 and 5.13 show the releases from the Motts Run reservoir for the critical periods of May 1965 – November 1966 and June 1980 – December 1981. Because the latter period is critical only for the Ni River reservoir, the Motts Run Reservoir releases are considerably greater and nearing the water treatment plant capacity of 24 mgd every month. Because of the 28-day limitation of February, the maximum yield is limited to 840 mg/mo. Tables 5.9 and 5.12 contain the releases from the Ni River Reservoir. Table 5.9 pattern is uniform in comparison to the pattern of releases given in Table 5.12. Because greater releases are available at the Motts Run Reservoir, the Ni River Reservoir flow for February 1981 is set at its maximum and other releases are brought in tune with the Motts Run releases so that a yield of 840 mg/mo is maintained. Because in the yield formulation given in Chapter 4, we maximize only the minimum of the releases, each monthly release need not be at its maximum and therefore alternative optima are possible.

There are three factors that control the yield, namely, the flows themselves, instream flow requirements, and the water treatment plant capacity. In this research we have studied only the historically worst drought scenario namely the nine-month period of May 1965-Jan 1966. The safe yield, therefore, provides an estimate of maximal withdrawal rate under the historically most stringent condition. This yield is dependent on the river flows available to the Spotsylvania County. However, if a drought worse than the historical sequence develops, this yield estimate will fail.

While equation 2.1 provides an yield estimated based on reservoir capacity, and cumulative inflow volume within a critical period, realistic estimates of the latter two parameters requires detailed examination of long sequences of data either historical or synthetically generated.

A new mathematical programming formulation capable of producing exact yield for the specified data has been developed. The large number of the binary variables involved in the formulation require an industry standard software for the solution. An examination of the optimal solution permits one to understand the binding constraints during the critical period and the role of the instream flow requirements and the nature of the flows themselves.

Even though the discussions have relied on the data and results pertaining to the Spotsylvania system, the methods are general and overcome the difficulties associated with the traditional analysis procedures.

Table 5.1 Safe Yield (MG per month) under Joint Operation of Motts Run, Hunting Run, and Ni River Reservoirs

Period	As is (Motts Run WT Plant Cap 12 mgd)	Expanded (Motts Run WT Plant Cap 24 mgd)
Ni Critical Period (June1980-Dec 1981)	500.5	840
Motts Critical Period (May 1965- Nov 1966)	504	816.5

Table 5.2 Output for Hunting Run Reservoir for Critical Period May 1965-Nov 1966*

Month	Rapidan Flow =1.486*FLOW(cfs) *Days*0.646317 (MG per month)	Storage Based Minimum Instream Condition at Rapidan (MG per month)	Inflow to the Reservoir After Pumpage and Instream Requirements (MG per month)	Storage at the Beginning of the month (MG)	Release from Reservoir (MG per month)
May	10152.7	15306.31	0.00	2196.00	321.22
June	4610.0	8899.17	0.00	1874.78	295.00
July	3096.4	6130.54	0.00	1579.78	256.56
August	2173.4	6130.54	0.00	1323.22	236.98
September	1852.7	5932.78	0.00	1086.24	96.24
October	3959.8	3065.27	744.00	990.00	253.62
November	2454.9	5932.78	0.00	1480.38	346.09
December	2099.0	6130.54	0.00	1134.29	144.29
January	2786.8	6130.54	0.00	990.00	272.48
February	20411.0	2768.63	672.00	717.52	0.00
March	17387.6	9195.81	678.48	1389.52	0.00
April	10804.8	14812.56	0.00	2068.00	0.00
May	20632.9	9195.81	258.05	2068.00	130.05
June	5618.5	8899.17	0.00	2196.00	0.00
July	2105.0	6130.54	0.00	2196.00	0.00
August	1039.1	6130.54	0.00	2196.00	257.65
September	14723.3	5932.78	257.65	1938.35	0.00
October	15958.5	6130.54	155.80	2196.00	155.80
November	9969.2	5932.78	0.00	2196.00	0.00

* No Spills Occur for the period.

Table 5.3 Output for Ni River Reservoir for Critical Period May 1965-Nov 1966

Month	Inflow to the Reservoir = (25/77.4)*Po River flow (cfs) * 0.646317*Days (MG per month)	Storage at the Beginning of the month (MG)	Release from Ni River Reservoir (MG per month)	Spill From Ni River Reservoir (MG per month)
May	255.0	750.00	153.35	101.65
June	149.7	750.00	164.00	0.00
July	146.3	735.70	132.00	0.00
August	117.1	750.00	132.00	0.00
September	57.9	735.10	144.00	0.00
October	97.1	649.00	132.00	0.00
November	58.6	614.10	144.00	0.00
December	71.8	528.70	132.00	0.00
January	173.4	468.50	186.00	0.00
February	777.4	455.90	168.00	315.30
March	498.3	750.00	186.00	312.30
April	419.6	750.00	180.00	239.60
May	454.9	750.00	186.00	268.90
June	81.4	750.00	144.00	0.00
July	44.9	687.40	186.00	0.00
August	5.0	546.30	132.00	0.00
September	411.5	419.30	180.00	0.00
October	515.8	650.80	132.00	284.60
November	157.2	750.00	180.00	0.00

Table 5.4 Output for Motts Run Reservoir for Critical Period May 1965-Nov 1966*

Month	Rappahannock River Flow =0.98*FLOW(cfs) *0.646317*Days (MG per month)	Storage Based Minimum Instream Condition at Rapahannock (MG per month)	Inflow to the Reservoir after Pumpage and Instream Requirements (MG per month)	Runoff from Motts Run Watershed (MG)	Release from Hunting Run Reservoir (MG per month)	Storage at the Beginning of the month (MG)	Release from Motts run Reservoir (MG per month)
May	17278.9	32656.12	0.00	29.43	321.22	1205.00	350.65
June	7695.7	18651.41	0.00	65.00	295.00	1205.00	360.00
July	5124.8	12842.07	0.00	115.44	256.56	1205.00	372.00
August	3769.9	12842.07	0.00	135.02	236.98	1205.00	372.00
September	2964.3	12427.81	0.00	263.76	96.24	1205.00	360.00
October	5438.9	12842.07	0.00	118.38	253.62	1205.00	372.00
November	3876.4	12427.81	0.00	13.91	346.09	1205.00	360.00
December	4025.2	12842.07	0.00	0.00	144.29	1205.00	372.00
January	5262.2	12842.07	0.00	141.24	272.48	977.29	372.00
February	43645.7	11599.29	280.00	133.99	0.00	1019.01	336.00
March	31632.2	18632.67	310.00	149.67	0.00	1097.00	351.67
April	22194.0	31602.70	0.00	43.10	0.00	1205.00	360.00
May	40232.3	12842.07	310.00	248.85	130.05	888.10	372.00
June	9652.9	18651.41	0.00	169.73	0.00	1205.00	360.00
July	2768.6	12842.07	0.00	17.04	0.00	1014.73	372.00
August	1500.1	12842.07	0.00	0.28	257.65	659.77	372.00
September	37338.4	12427.81	0.00	320.30	0.00	545.70	324.00
October	36030.4	12842.07	0.00	879.20	155.80	542.00	372.00
November	15961.4	12427.81	284.31	75.69	0.00	1205.00	360.00

*No Spills Occur for the period.

Table 5.5 Output for Hunting Run Reservoir for Critical Period May 1965-Nov 1966*

Month	Rapidan Flow =1.486*FLOW(cfs) *Days*0.646317 (MG per month)	Storage Based Minimum Instream Condition at Rapidan (MG per month)	Inflow to the Reservoir After Pumpage and Instream Requirements (MG per month)	Storage at the Beginning of the month (MG)	Release from Reservoir (MG per month)
May	10152.7	15306.31	0.00	2196.00	656.00
June	4610.0	2966.39	720.00	1540.00	89.47
July	3096.4	6130.54	0.00	2170.53	0.00
August	2173.4	6130.54	0.00	2170.53	829.48
September	1852.7	5932.78	0.00	1341.05	1035.71
October	3959.8	3065.27	744.00	305.35	169.35
November	2454.9	5932.78	0.00	880.00	880.00
December	2099.0	3065.27	0.00	0.00	0.00
January	2786.8	3065.27	0.00	0.00	0.00
February	20411.0	2768.63	672.00	0.00	672.00
March	17387.6	6130.54	744.00	0.00	744.00
April	10804.8	5932.78	720.00	0.00	0.00
May	20632.9	6130.54	717.78	720.00	394.33
June	5618.5	2966.39	720.00	1043.45	912.27
July	2105.0	3065.27	0.00	851.18	123.96
August	1039.1	3065.27	0.00	727.22	683.72
September	14723.3	2966.39	720.00	43.50	0.00
October	15958.5	3065.27	744.00	763.50	627.50
November	9969.2	2966.39	720.00	880.00	344.31

* No Spills Occur for the period.

Table 5.6 Output for Ni River Reservoir for Critical Period May 1965-Nov 1966

Month	Inflow to the Reservoir = (25/77.4)*Po River flow (cfs) * 0.64617*Days (MG per month)	Storage at the Beginning of the month (MG)	Release from Ni River Reservoir (MG per month)	Spill From Ni River Reservoir (MG per month)
May	255.0	750.00	186.00	69.00
June	149.7	750.00	180.00	0.00
July	146.3	719.70	186.00	0.00
August	117.1	680.00	186.00	0.00
September	57.9	611.10	180.00	0.00
October	97.1	489.00	186.00	0.00
November	58.6	400.10	180.00	0.00
December	71.8	278.70	186.00	0.00
January	173.4	164.50	186.00	0.00
February	777.4	151.90	168.00	11.30
March	498.3	750.00	186.00	312.30
April	419.6	750.00	180.00	239.60
May	454.9	750.00	186.00	268.90
June	81.4	750.00	104.33	0.00
July	44.9	727.07	72.47	0.00
August	5.0	699.50	186.00	0.00
September	411.5	518.50	180.00	0.00
October	515.8	750.00	186.00	329.80
November	157.2	750.00	180.00	0.00

Table 5.7 Output for Motts Run Reservoir for Critical Period May 1965-Nov 1966*

Month	Rappahannock River Flow =0.98*FLOW(cfs) *0.646317*Days (MG per month)	Storage Based Minimum Instream Condition at Rapahannock (MG per month)	Inflow to the Reservoir after Pumpage and Instream Requirements (MG per month)	Runoff from Motts Run Watershed (MG)	Release from Hunting Run Reservoir (MG per month)	Storage at the Beginning of the month (MG)	Release from Motts run Reservoir (MG per month)
May	17278.9	32656.12	0.00	29.43	656.00	1205.00	685.43
June	7695.7	18651.41	0.00	65.00	89.47	1205.00	636.47
July	5124.8	12842.07	0.00	115.44	0.00	723.00	630.47
August	3769.9	6431.05	0.00	135.02	829.48	207.97	630.47
September	2964.3	6223.60	0.00	263.76	1035.71	542.00	636.47
October	5438.9	12842.07	0.00	118.38	169.35	1205.00	630.47
November	3876.4	12427.81	0.00	13.91	880.00	862.26	636.47
December	4025.2	12842.07	0.00	0.00	0.00	1119.70	630.47
January	5262.2	6431.05	0.00	141.24	0.00	489.23	630.47
February	43645.7	5808.69	280.00	133.99	672.00	0.00	648.47
March	31632.2	12842.07	310.00	149.67	744.00	437.52	630.47
April	22194.0	18651.41	300.00	43.10	0.00	1010.72	720.00
May	40232.3	12842.07	310.00	248.85	394.33	633.82	744.00
June	9652.9	18651.41	0.00	169.73	912.27	843.00	720.00
July	2768.6	12842.07	0.00	17.04	123.96	1205.00	744.00
August	1500.1	6431.05	0.00	0.28	683.72	602.00	744.00
September	37338.4	6223.60	300.00	320.30	0.00	542.00	720.00
October	36030.4	6431.05	0.00	879.20	627.50	442.30	744.00
November	15961.4	12427.81	300.00	75.69	344.31	1205.00	720.00

*No Spills Occur for the period.

Table 5.8 Output for Hunting Run Reservoir for Critical Period June 1980-Dec 1981*

Month	Rapidan Flow =1.486*FLOW(cfs) *Days*0.646317 (MG per month)	Storage Based Minimum Instream Condition at Rapidan (MG per month)	Inflow to the Reservoir After Pumpage and Instream Requirements (MG per month)	Storage at the Beginning of the month (MG)	Release from Reservoir (MG per month)
June	7721.8	8899.17	0.00	2196.00	0.00
July	5835.6	6130.54	0.00	2196.00	510.15
August	5061.5	6130.54	0.00	1685.85	0.00
September	2403.0	5932.78	0.00	1685.85	0.00
October	2968.4	6130.54	0.00	1685.85	172.87
November	4638.9	5932.78	0.00	1512.98	632.98
December	4287.3	6130.54	0.00	880.00	251.53
January	3304.8	3065.27	239.53	628.47	0.00
February	16673.0	2768.63	672.00	868.00	0.00
March	7383.8	9195.81	0.00	1540.00	0.00
April	6050.7	8899.17	0.00	1540.00	1533.80
May	8723.6	6130.54	0.00	6.20	0.00
June	9969.2	2966.39	720.00	6.20	0.00
July	11581.8	3065.27	677.89	726.20	304.09
August	3215.5	3065.27	150.23	1100.00	200.64
September	4177.9	5932.78	0.00	1049.59	59.59
October	5716.5	6130.54	0.00	990.00	110.00
November	4725.3	5932.78	0.00	880.00	0.00
December	6758.5	3065.27	744.00	880.00	0.00

* No Spills Occur for the period.

Table 5.9 Output for Ni River Reservoir for Critical Period June 1980-Dec 1981*

Month	Inflow to the Reservoir = (25/77.4)*Po River flow (cfs) * 0.646317*Days (MG per month)	Storage at the Beginning of the month (MG)	Release from Ni River Reservoir (MG per month)
June	120.9	750.00	140.48
July	46.3	730.42	128.48
August	13.8	648.23	128.48
September	5.9	533.55	140.48
October	29.3	398.97	128.48
November	96.4	299.78	140.48
December	79.0	255.70	128.48
January	67.3	206.22	128.48
February	347.8	145.03	164.48
March	163.1	328.35	128.48
April	169.7	362.97	140.48
May	342.3	392.18	128.48
June	43.7	606.00	140.48
July	58.9	509.22	128.48
August	21.2	439.63	128.48
September	8.6	332.35	140.48
October	44.4	200.47	128.48
November	24.1	116.38	140.48
December	227.8	0.00	186.00

*No Spills Occur for the period

Table 5.10 Output for Motts Run Reservoir for Critical Period June 1980-Dec 1981*

Month	Rappahannock River Flow =0.98*FLOW(cfs) *0.646317*Days (MG per month)	Storage Based Minimum Instream Condition at Rapahannock (MG per month)	Inflow to the Reservoir after Pumpage and Instream Requirements (MG per month)	Runoff from Motts Run Watershed (MG)	Release from Hunting Run Reservoir (MG per month)	Storage at the Beginning of the month (MG)	Release from Motts run Reservoir (MG per month)
June	17671.6	18651.41	0.00	27.12	0.00	1205.00	360.00
July	10328.1	12842.07	0.00	51.95	510.15	872.12	372.00
August	9974.6	12842.07	0.00	140.69	0.00	1062.22	372.00
September	3553.3	12427.81	0.00	71.09	0.00	830.91	360.00
October	3927.0	12842.07	0.00	139.13	172.87	542.00	372.00
November	7467.7	12427.81	0.00	128.36	632.98	482.00	360.00
December	7147.2	12842.07	0.00	68.22	251.53	883.34	372.00
January	5831.6	12842.07	0.00	0.00	0.00	831.09	372.00
February	31053.9	5808.69	101.01	28.55	0.00	459.09	336.00
March	12173.8	12842.07	0.00	119.35	0.00	252.65	372.00
April	11154.0	12427.81	0.00	31.20	1533.80	0.00	360.00
May	15884.8	32656.12	0.00	130.90	0.00	1205.00	372.00
June	14137.3	18651.41	0.00	157.14	0.00	963.90	360.00
July	11938.1	12842.07	0.00	511.87	304.09	761.04	372.00
August	7107.9	12842.07	0.00	171.36	200.64	1205.00	372.00
September	7087.6	12427.81	0.00	86.06	59.59	1205.00	360.00
October	8266.4	12842.07	0.00	232.32	110.00	990.65	372.00
November	7353.7	12427.81	0.00	43.43	0.00	960.97	360.00
December	12213.0	12842.07	0.00	45.16	0.00	644.40	372.00

*No Spills Occur for the period.

Table 5.11 Output for Hunting Run Reservoir for Critical Period June 1980-Dec 1981*

Month	Rapidan Flow =1.486*FLOW(cfs) *Days*0.646317 (MG per month)	Storage Based Minimum Instream Condition at Rapidan (MG per month)	Inflow to the Reservoir After Pumpage and Instream Requirements (MG per month)	Storage at the Beginning of the month (MG)	Release from Reservoir (MG per month)
June	7721.8	8899.17	0.00	2196.00	186.73
July	5835.6	6130.54	0.00	2009.27	1174.05
August	5061.5	3065.27	744.00	835.22	589.22
September	2403.0	5932.78	0.00	990.00	0.00
October	2968.4	6130.54	0.00	990.00	464.11
November	4638.9	2966.39	720.00	525.89	365.89
December	4287.3	3065.27	744.00	880.00	1164.53
January	3304.8	3065.27	239.53	459.47	51.00
February	16673.0	2768.63	672.00	648.00	0.00
March	7383.8	9195.81	0.00	1320.00	386.10
April	6050.7	5932.78	117.92	933.90	1051.82
May	8723.6	6130.54	744.00	0.00	723.08
June	9969.2	2966.39	720.00	20.92	740.92
July	11581.8	3065.27	744.00	0.00	0.00
August	3215.5	3065.27	150.23	744.00	265.92
September	4177.9	2966.39	720.00	628.31	633.94
October	5716.5	3065.27	744.00	714.37	578.37
November	4725.3	5932.78	0.00	880.00	549.88
December	6758.5	3065.27	744.00	330.12	1074.12

* No Spills Occur for the period.

Table 5.12 Output for Ni River Reservoir for Critical Period June 1980-Dec 1981*

Month	Inflow to the Reservoir = (25/77.4)*Po River flow (cfs) * 0.646317*Days (MG per month)	Storage at the Beginning of the month (MG)	Release from Ni River Reservoir (MG per month)
June	120.9	750.00	144.15
July	46.3	726.75	96.00
August	13.8	677.05	96.00
September	5.9	594.85	120.00
October	29.3	480.75	176.76
November	96.4	333.29	180.00
December	79.0	249.69	186.00
January	67.3	142.69	186.00
February	347.8	23.99	168.00
March	163.1	203.79	96.00
April	169.7	270.89	180.00
May	342.3	260.59	96.00
June	43.7	506.89	179.79
July	58.9	370.80	96.00
August	21.2	333.70	96.00
September	8.6	258.90	120.00
October	44.4	147.50	96.00
November	24.1	95.90	120.00
December	227.8	0.00	186.00

*No Spills Occur for the period.

Table 5.13 Output for Motts Run Reservoir for Critical Period June 1980-Dec 1981*

Month	Rappahannock River Flow=0.98*FLOW(cfs) *0.646317*Days (MG per month)	Storage Based Minimum Instream Condition at Rapahannock (MG per month)	Inflow to the Reservoir after Pumpage and Instream Requirements (MG per month)	Runoff from Motts Run Watershed (MG)	Release from Hunting Run Reservoir (MG per month)	Storage at the Beginning of the month (MG)	Release from Motts run Reservoir (MG per month)
June	17671.6	18651.41	0.00	27.12	186.73	1205.00	695.85
July	10328.1	12842.07	0.00	51.95	1174.05	723.00	744.00
August	9974.6	12842.07	0.00	140.69	589.22	1205.00	744.00
September	3553.3	12427.81	0.00	71.09	0.00	1190.91	720.00
October	3927.0	6431.05	0.00	139.13	464.11	542.00	663.24
November	7467.7	12427.81	0.00	128.36	365.89	482.00	660.00
December	7147.2	6431.05	310.00	68.22	1164.53	316.25	654.00
January	5831.6	12842.07	0.00	0.00	51.00	1205.00	654.00
February	31053.9	11599.29	280.00	28.55	0.00	602.00	672.00
March	12173.8	12842.07	0.00	119.35	386.10	238.55	744.00
April	11154.0	12427.81	0.00	31.20	1051.82	0.00	660.00
May	15884.8	12842.07	310.00	130.90	723.08	423.02	744.00
June	14137.3	18651.41	0.00	157.14	740.92	843.00	660.21
July	11938.1	12842.07	0.00	511.87	0.00	1080.85	744.00
August	7107.9	12842.07	0.00	171.36	265.92	848.72	744.00
September	7087.6	12427.81	0.00	86.06	633.94	542.00	720.00
October	8266.4	12842.07	0.00	232.32	578.37	542.00	744.00
November	7353.7	12427.81	0.00	43.43	549.88	608.69	720.00
December	12213.0	12842.07	0.00	45.16	1074.12	482.00	744.00

*No Spills Occur for the period

6. El Nino / Southern Oscillation (ENSO) Phenomenon

6.1 Introduction

In earlier chapters, safe yield for a multi-reservoir system was calculated using a linear optimization model. The model uses the inflows from the river to the reservoirs. These inflows are dependent on the climate of the region. ENSO (El Nino/Southern Oscillation) phenomena is generally considered to be a major factor in the rainfall patterns and hence the river streamflows. In the historical record the interval between the events has varied from 2 to 7 years [http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html]. The changes in streamflow reflect in the inflows to the reservoir and hence in the safe yield of the reservoir system. Section 6.2.1 gives the definitions of the important terms and explains the ENSO. Climatic impacts on the global and U.S. climate are discussed in the section 6.2.2. Further the definitions of ENSO indices and identification of ENSO events are discussed in sections 6.2.3 and sections 6.2.4, respectively.

6.2 ENSO Phenomenon

6.2.1 Definitions

ENSO is the name given to a phenomenon that involves changes in ocean-atmosphere interaction in tropical pacific region leading to teleconnections, long distance cause-and-effect relationships, and impacts on weather around the globe. The ENSO term is composed of two phenomena (1) El Nino and (2) Southern Oscillation. El Nino is appearance of unusually warm water in the Pacific Ocean off the coast of South America. The increase in temperature is around 1-3 degrees for El Nino years and decrease in temperatures is around 1-2 degrees for La Nina years (Table 6.1). For example, Table 6.1 shows the mean monthly temperatures and anomalies (deviation from the mean) for Nino3 region (5S-5N, 150W-90W, Figure 6.5) (which also covers coast of Peru), for Neutral (1996), El Nino (1997) and La Nina (1998) years respectively. A significant increase in the temperatures is found for El Nino year (1997) where a drop in temperature is noticed for La Nina year (1998).

Table 6.1 Monthly SST and Anomalies (^{o}C) for 1996-1998, for Nino 3 region (source: http://www.cpc.ncep.noaa.gov/data/indices/)

Year	Month	Nino 3	Anomaly
1996	Jan	24.96	-0.65
1996	Feb	25.72	-0.64
1996	Mar	26.71	-0.38
1996	Apr	26.72	-0.68
1996	May	26.33	-0.73
1996	June	25.89	-0.49
1996	Jul	25.35	-0.23
1996	Aug	24.6	-0.35
1996	Sept	24.37	-0.46
1996	Oct	24.37	-0.52
1996	Nov	24.38	-0.57
1996	Dec	24.2	-0.88
1997	Jan	24.7	-0.91
1997	Feb	25.75	-0.61
1997	Mar	26.98	-0.11
1997	Apr	27.59	0.18
1997	May	28.06	**1.00**
1997	June	28.14	**1.76**
1997	Jul	28.01	**2.43**
1997	Aug	27.84	**2.89**
1997	Sept	27.84	**3.01**
1997	Oct	28.17	**3.29**
1997	Nov	28.55	**3.59**
1997	Dec	28.76	**3.68**
1998	Jan	28.94	3.32
1998	Feb	28.93	2.57
1998	Mar	29.14	2.05
1998	Apr	29.09	1.68
1998	May	28.17	1.11
1998	June	26	**-0.37**
1998	Jul	25.24	**-0.35**
1998	Aug	24.63	**-0.33**
1998	Sept	24.19	**-0.64**
1998	Oct	24.06	**-0.83**
1998	Nov	24.11	**-0.85**
1998	Dec	23.86	**-1.22**

a. Neutral (or Normal) Years

All the years other than El Nino and La Nina years are called the Neutral (or normal) years. During Neutral (or Normal) years the trade winds blow from east (Peru) to western pacific region (Australia)(Figure 6.1). Trade winds are a consistent system of prevailing winds occupying most of the tropics, constituting the major component of the general circulation of the atmosphere, and blowing towards northeast in the Northern Hemisphere and southeasterly in the Southern Hemisphere. These winds carry the warm waters of the eastern Pacific surface to the western Pacific region thereby increasing the surface of western Pacific to about 0.5 m higher than eastern pacific region (Coast of Peru) [see details at : http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html]. The sea surface temperature in the western pacific is around 8 ^{o}C higher than that in eastern Pacific [http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html]. The position of 'thermocline' causes this temperature difference by providing upwelling of cold water in the eastern pacific. 'Thermocline' is a layer of water in an ocean where the temperature gradient is greater than that of the warmer layer above and the colder layer below.

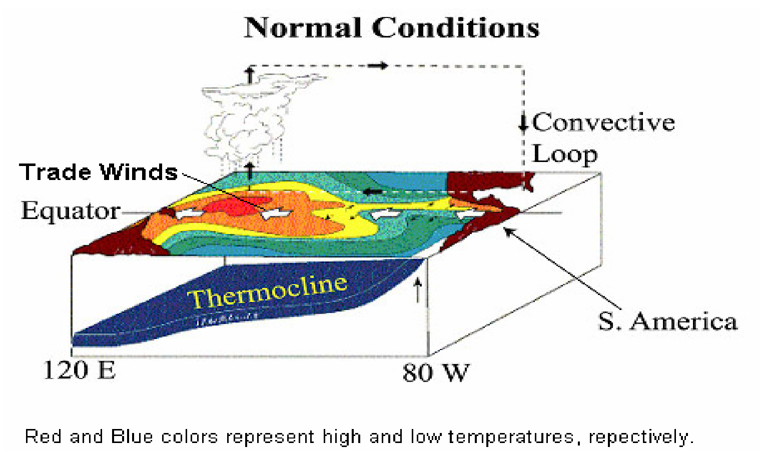


Figure 6.1 a. Ocean-Atmosphere interactions in Tropical Pacific during Neutral Years

[Source: http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html]

b. El Nino years

During El Nino years, trade winds change their pattern by getting weakened in western and central pacific region which causes the thermocline drop in eastern pacific (Figure 6.1 b). For example, the thermocline dropped to 150 m in 1982-83 El Nino after being at 50 m in normal conditions at eastern pacific [http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html].

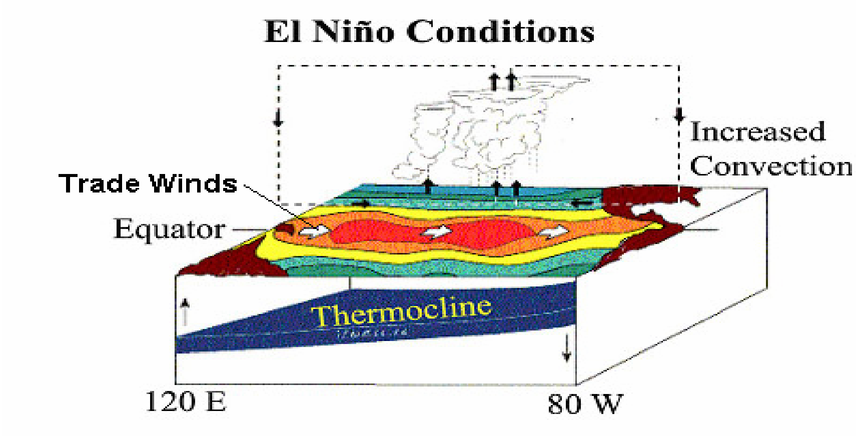


Figure 6.1 b. Ocean-Atmosphere interactions in Tropical Pacific during El Nino years [Source: http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html]

This thermocline drop results increase in temperature of sea surface at eastern pacific hence changing the rainfall pattern in the eastern pacific. This change causes flooding in eastern coast (e.g. Peru) and drought in western pacific (e.g. Indonesia). This phenomenon is referred to as El Nino, meaning 'the Christ child' in Spanish, since the warm current appears off the coast of Peru at Christmas time (December) during this event.

To show the changes in the sea surface temperatures during El Nino/ La Nina periods, SST anomalies in region Nino1+2 (0-10S; 80-90W)., Nino3(5S-5N; 150W-90W), Nino 3.4(5S-5N; 170W-120W) and Nino 4(5S-5N; 160E-150W) are plotted in Figure 6.2 a, b, c and d. All the years for which have SST anomaly of greater than +1^{o}C are classified as El Nino years and years with SST anomalies greater than –1^{o}C are classified as La Nina events. El Nino / La Nina years are indicated in red and blue respectively. 1982-1983 which is reported as one of the most severe El Nino event in the literature is spotted in all the plots. 1988 and 1955 are found to be most severe of the La Nina events in all the regions except Nino1+2. Furthermore, on comparing the regions it can be seen that greater differences in the temperatures are obtained in Nino3 (5S-5N; 150W-90W) region than all other regions. Proximity of streamflow location to the Nino regions might be a factor in choosing the corresponding Nino regions for analysis. For example, Nino1+2 region is closer to Peru coastline whereas Australian regions are closer to Nino 4 region. Nino1+2 region covers nearly all the El Nino and La Nina events after 1950 by this classification method hence can be used as the best indicator of the El Nino/ La Nina events.

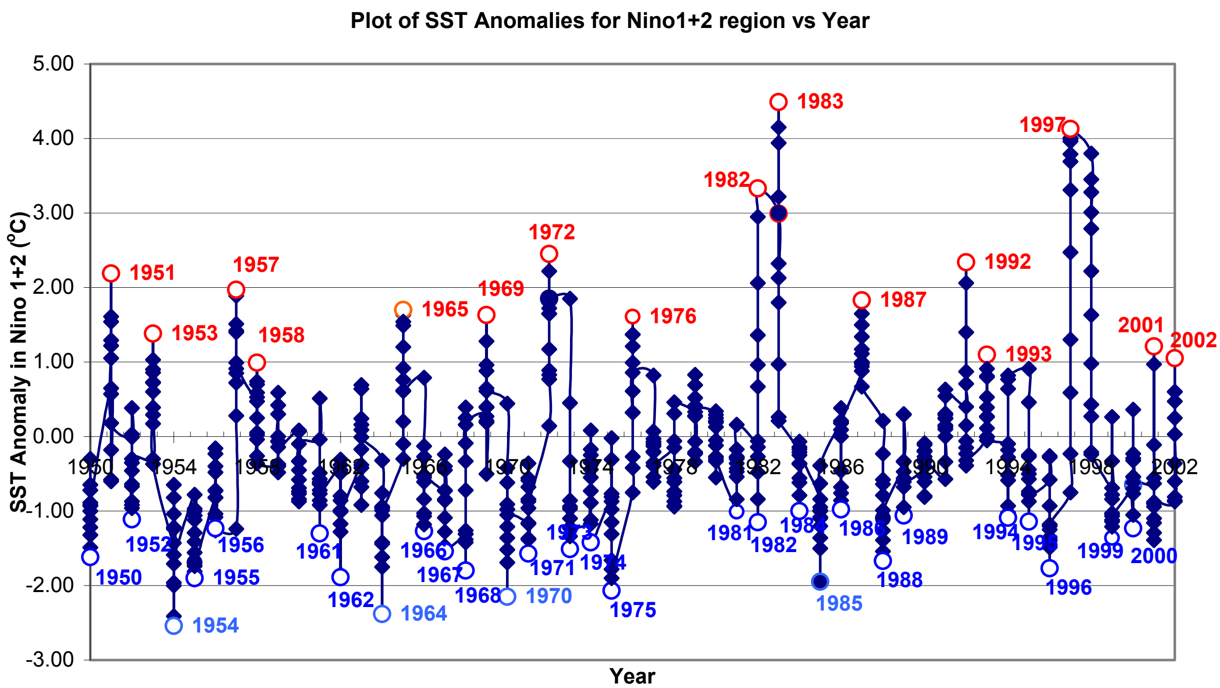


Figure 6.2 a

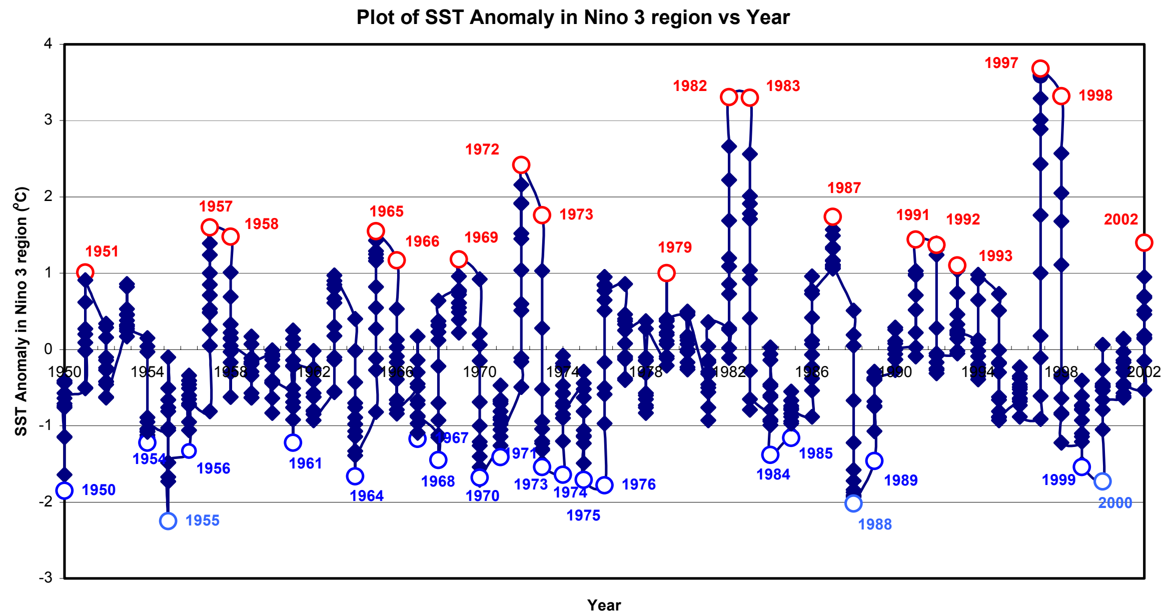


Figure 6.2 b

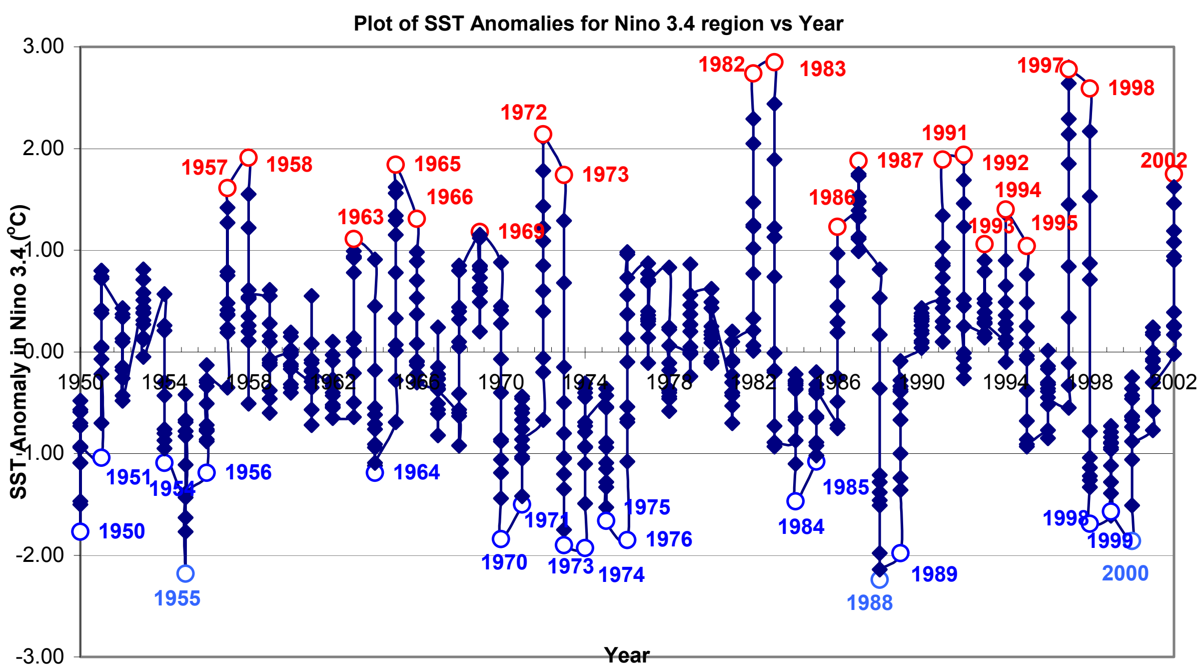


Figure 6.2 c

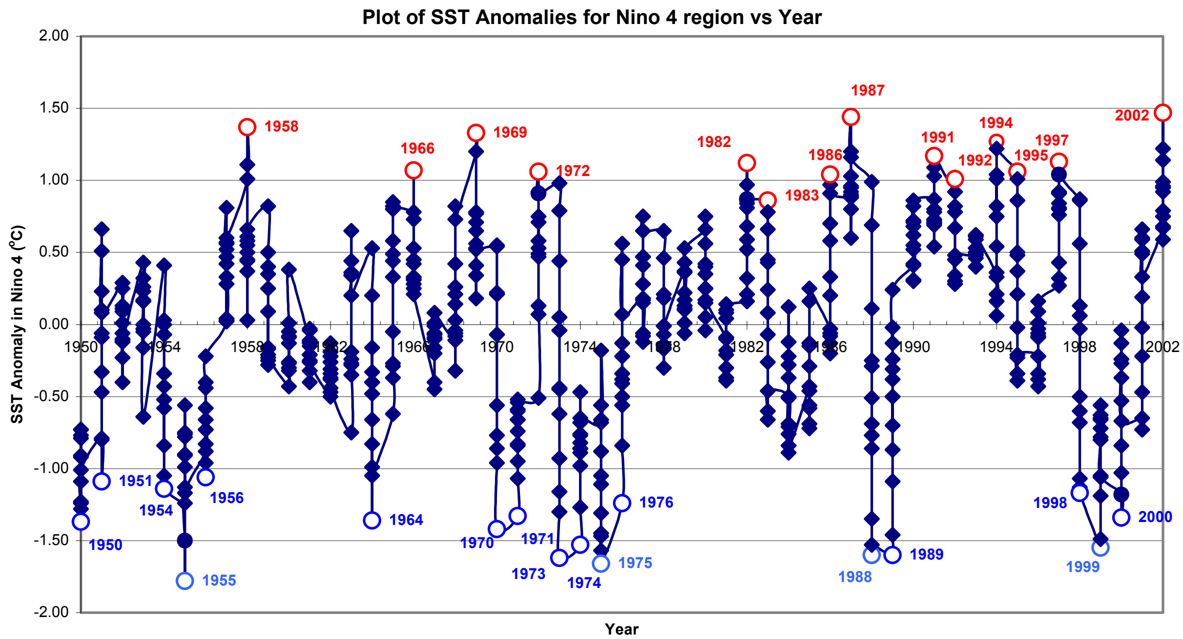


Figure 6.2 d

Figure 6.2 Plots of SST Anomalies vs Year for a. Nino1+2 b. Nino 3 region b. Nino 3.4 d. Nino4 regions

b. La Nina years

La Nina, meaning 'the little girl' in Spanish, is the colder counterpart of El Nino. During La Nina, the sea surface temperatures are colder (around 3^{o} C lower) than normal in the western Pacific [http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html]. These result in reversal in the rainfall pattern as compared to El Nino condition where the sea surface temperature is warmer than normal conditions in eastern pacific.

For example, sea surface temperature patterns are shown in Figure 6.2 a, 6.2 b, and 6.2 c [Source: http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html]. Temperatures show an eastern shift of higher temperature regions during El Nino year as compared to normal conditions along the Pacific region (Figure 6.3 b). La Nina Event is marked by the shift of the higher temperature regions towards the western Pacific regions (Figure 6.3 c).

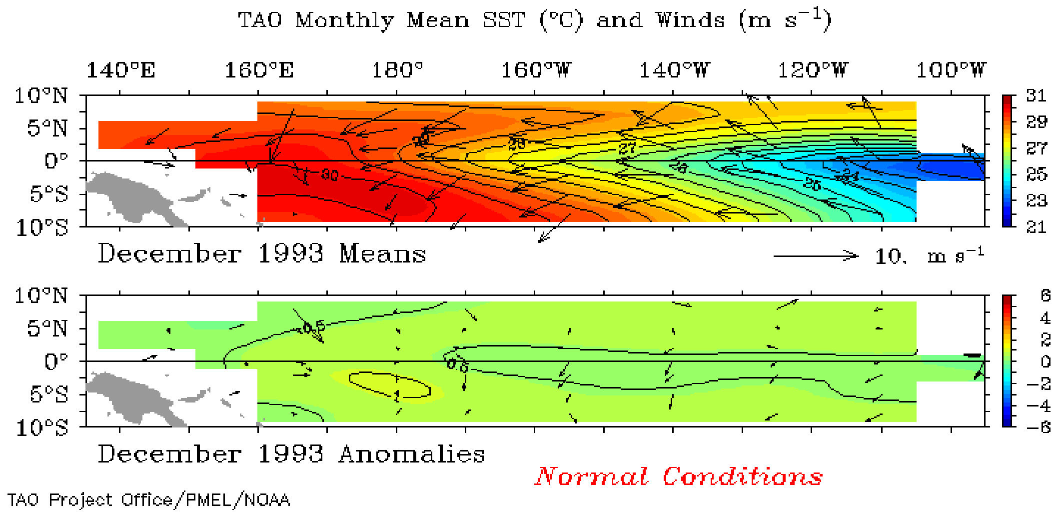


Figure 6.3 a. Sea Surface Temperature Means and Anomalies in Normal Conditions

[http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html]

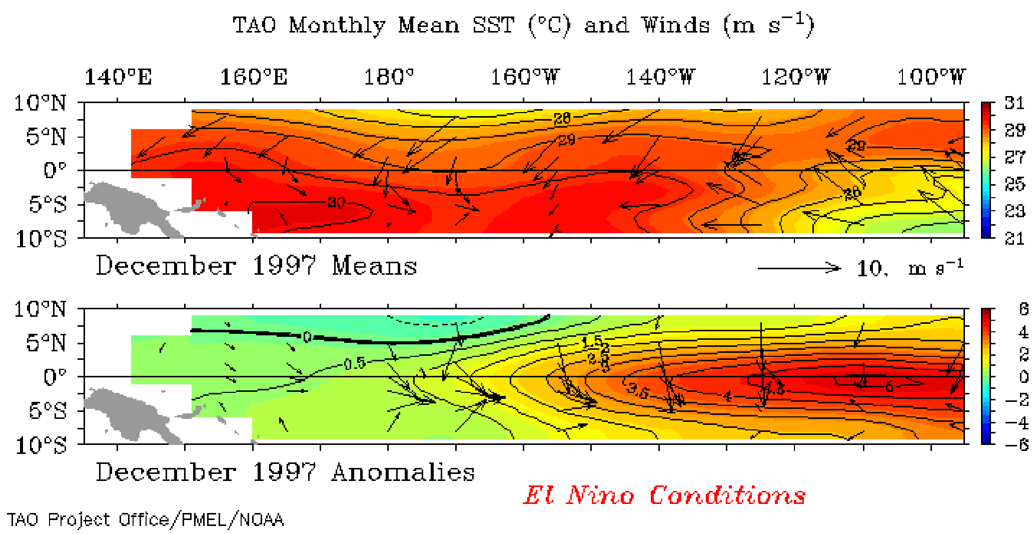


Figure 6.3 b. Sea Surface Temperature Means and Anomalies in El Nino Conditions

[http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html]

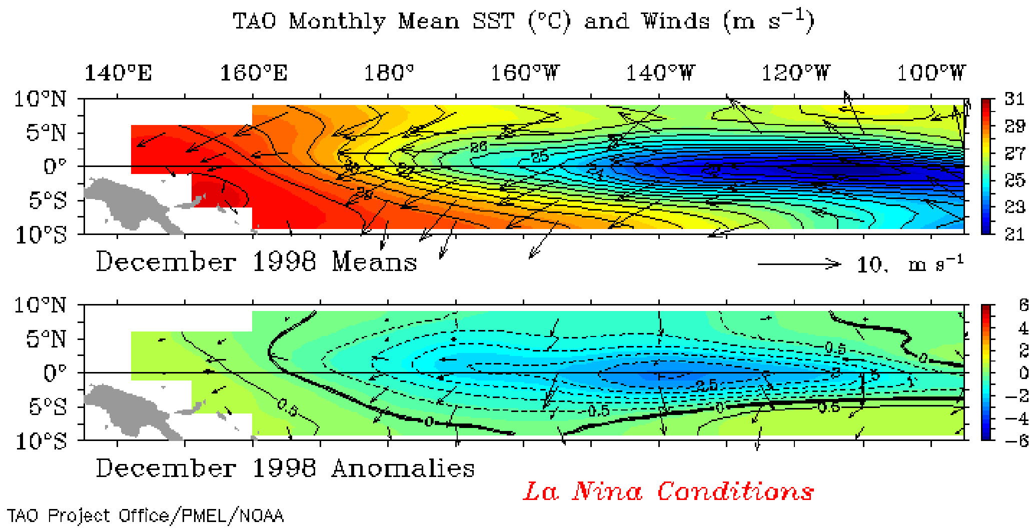


Figure 6.3 c. Sea Surface Temperature Means and Anomalies in La Nina Conditions [http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html]

The system oscillates between warm (El Nino) to neutral (or La Nina) conditions with an on average every 3-5 years. However, in the historical record the interval between the events has varied from 2 to 7 years [http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html].

Table 6.2 shows the occurrences of ENSO events after 1950 till 2002 according to various classifications (section 6.4). It can be seen that al these classification does not agree to each other in most of the cases.

Table 6.2 ENSO Years since 1950, Based on Various Classifications

		Based on SST	
	Based on SOI	Based on Trenberth(1997)	Based on NOAA
1950	La Nina	La Nina	La Nina
1951	El Nino	La Nina	El Nino
1952	Neutral	Neutral	Neutral
1953	El Nino	Neutral	El Nino
1954	Neutral	Neutral	La Nina
1955	La Nina	La Nina	La Nina
1956	La Nina	La Nina	La Nina
1957	El Nino	El Nino	El Nino
1958	Neutral	El Nino	El Nino
1959	Neutral	Neutral	Neutral
1960	Neutral	Neutral	Neutral

1961	Neutral	Neutral	Neutral
1962	Neutral	Neutral	Neutral
1963	El Nino	Neutral	Neutral
1964	La Nina	Neutral	La Nina
1965	El Nino	La Nina	El Nino
1966	Neutral	El Nino	Neutral
1967	Neutral	Neutral	Neutral
1968	Neutral	La Nina	Neutral
1969	El Nino	El Nino	El Nino
1970	La Nina	El Nino	La Nina
1971	La Nina	La Nina	La Nina
1972	El Nino	La Nina	El Nino
1973	La Nina	El Nino	La Nina
1974	La Nina	La Nina	La Nina
1975	La Nina	La Nina	La Nina
1976	Neutral	La Nina	El Nino
1977	El Nino	El Nino	Neutral
1978	Neutral	Neutral	Neutral
1979	Neutral	Neutral	Neutral
1980	Neutral	Neutral	Neutral
1981	Neutral	Neutral	Neutral
1982	El Nino	El Nino	El Nino
1983	Neutral	El Nino	El Nino
1984	Neutral	La Nina	La Nina
1985	Neutral	La Nina	La Nina
1986	Neutral	Neutral	El Nino
1987	El Nino	El Nino	El Nino
1988	La Nina	El Nino	La Nina
1989	Neutral	La Nina	La Nina
1990	Neutral	Neutral	Neutral
1991	El Nino	El Nino	El Nino
1992	Neutral	El Nino	El Nino
1993	El Nino	El Nino	Neutral
1994	El Nino	Neutral	El Nino
1995	Neutral	El Nino	Neutral
1996	Neutral	La Nina	Neutral
1997	El Nino	El Nino	El Nino
1998	La Nina	El Nino	La Nina
1999	Neutral	La Nina	La Nina
2000	La Nina	La Nina	La Nina
2001	Neutral	La Nina	Neutral
2002	El Nino	El Nino	El Nino

6.2.2 Climatic Impacts

ENSO phenomenon has been attributed to cause shifts in precipitation patterns around the globe. Figure 6.4 a and Figure 6.4 b show potential climatic effects of ENSO in many different regions of the world during summer and winter, in an El Nino year. The shifting of precipitation patterns causes much of Southeast Asia and parts of Australia to experience dry conditions during an ENSO event, leading to drought conditions in many areas. This is especially devastating to countries which depend on rainfall for their crops [http://www.pmel.noaa.gov/tao/elnino/nino-home.html].

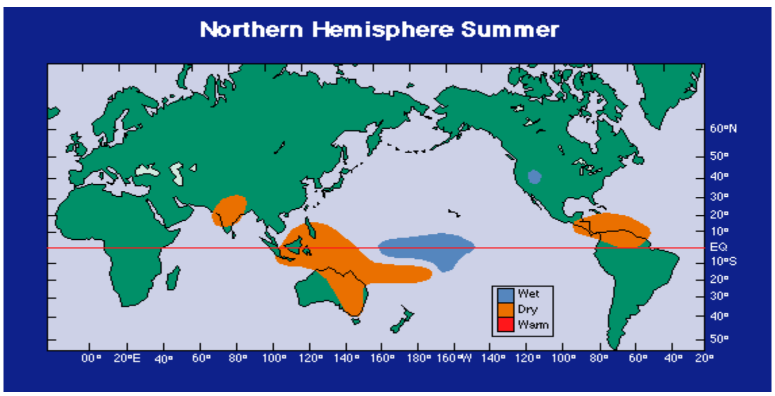


Figure 6.4 a

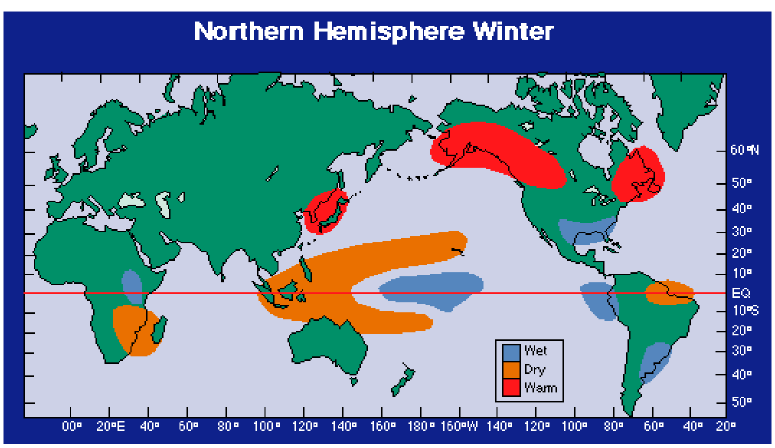


Figure 6.4 b

Figure 6.4 Impacts of El Nino on the World Precipitation a. summer and b. winter [Source: http://www.pmel.noaa.gov/tao/elnino/impacts.html]

Under normal conditions, the northward-blowing winds off South America cause nutrient-rich waters to upwell from below the shallow, warm surface layer. The nutrients (mainly phosphates and nitrates) provide a plentiful supply of food for photosynthesizing plankton, on which the fish feed. During El Nino, however, the thicker surface layer acts as a barrier to effective upwelling by the coastal winds. The non-enriched surface waters are poor in nutrients and cannot support the normally productive coastal ecosystem. Fish populations are decimated as great numbers migrate to less-affected areas in search of food, resulting in temporarily reduced yields for the countries in the region [Source: http://www.crystalinks.com/elnino.html].

Also significant is the rise in hurricane activity in Pacific Ocean [for details see: http://lumahai.soest.hawaii.edu/Enso/index.html], which usually occurs during an ENSO event. These hurricanes can bring strong winds, large amounts of precipitation, and storm surges that can cause beach erosion. Following sections give a brief description of ENSO impacts around the globe in general and U.S. climate in particular.

a. Global Impacts: Abnormally heavy rainfall over equatorial Pacific warm waters extends into coastal Ecuador and northern Peru, while drought conditions often prevail in parts of Australia, Malaysia, Indonesia, and Micronesia, Africa, northeast Brazil, Central America and tropical Africa. Rice and cotton, two of the primary crops grown in northern Peru, are highly sensitive to the quantities and timing of rainfall. Rice thrives on wet conditions during the growing season followed by drier conditions during the ripening phase. Cotton, with its deeper root system, can tolerate drier weather. Hence, El Nino weather might decrease the crop sown in the opposite pattern.

b. Impacts on US Climate: The impacts of El Nino over the United States vary from one event to the next and they tend to be restricted to winter and early spring. On average, Hawaii tends to be dry; Alaska, the Pacific Northwest and the Northern Plains, mild and dry, and the South, wet (Figure 6.5). La Nina years tend to be marked by the opposite kinds of climate phenomena in the above regions. La Nina often features drier than normal conditions in the Southwest in late summer through the subsequent winter. Drier than normal conditions also typically occur in Central Plains and Southeast U.S. during fall and winter, respectively.

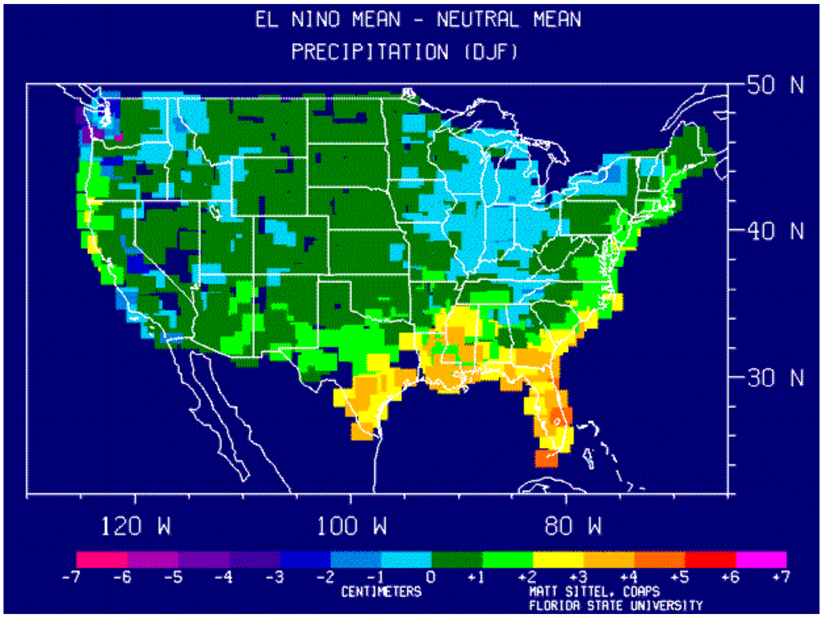


Figure 6.5 Impact of El Nino on the U.S. Precipitation during winter [Source: http://www.pmel.noaa.gov/tao/elnino/impacts.html]

In contrast, the Pacific Northwest is more likely to be wetter than normal in the late fall and early winter with the presence of a well-established La Nina. Additionally, on average La Nina winters are warmer than normal in the Southeast and colder than normal in the Northwest [http://www.pmel.noaa.gov/tao/elnino/nino-home.html].

6.3 ENSO Indices

The intensity of ENSO phenomenon is often represented by a number of indices, for example Southern Oscillation Index (SOI), Nino1+2 SST index, Nino 3 SST index etc. The commonly used indices are based on the use of sea level pressure and sea surface temperature observations in certain key geographic locations in mid-Pacific region. A description of these indices is as follows:

6.3.1 Pressure based index

Southern Oscillation Index (SOI) is the index based on the sea surface pressure at two points namely, Darwin and Tahiti, in the Pacific Ocean. There are different methods for calculating SOI index, which is the standardized anomaly of the mean sea level pressure difference between Tahiti and Darwin (Tahiti is located at 149.6°W, 17.5°S; Darwin at 130.9°E, 12.4°S) (Figure 6.6). There are mainly two techniques that are used to compute the SOI. These are reviewed as follows:

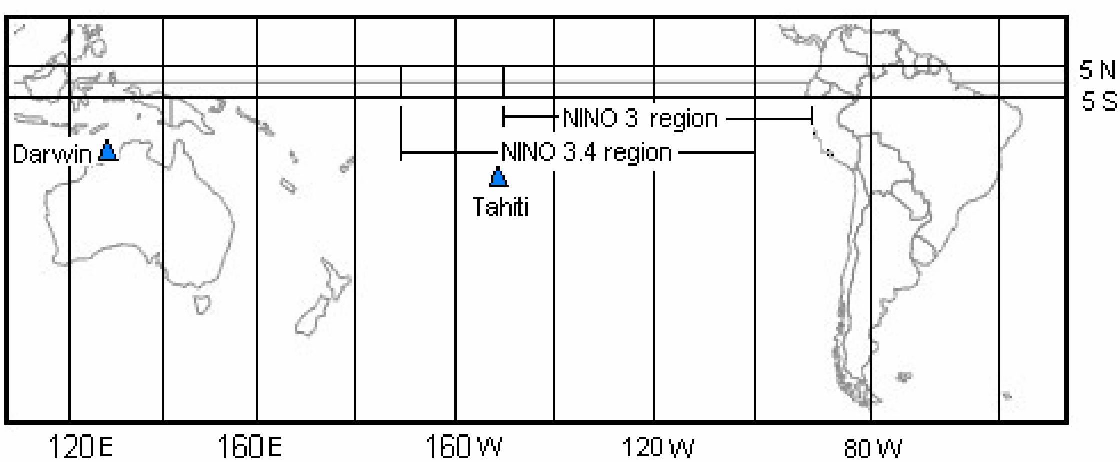


Figure 6.6 Regions for El Nino Indices

i. Method Used by National Oceanic and Atmospheric Administration (NOAA):

Method used by NOAA to calculate SOI is as follows:

Suppose SLP = Sea Level Pressure

TahitiAnomaly = (actual (SLP) – mean (SLP))

DarwinAnomaly = (actual (SLP) – mean (SLP))

(The anomalies are departures from the 1951-1980 base period)

N - number of months

$$\text{Standard Deviation Tahiti} = \sqrt{\frac{\Sigma(TahitiAnomaly)^2}{N}}$$

$$\text{Standardized Tahiti } (StdTahiti) = \frac{\text{(Actual Tahiti (SLP) - Mean Tahiti (SLP))}}{\text{Standard Deviation Tahiti}}$$

$$\text{Standard Deviation Darwin} = \sqrt{\frac{\Sigma(DarwinAnomaly)^2}{N}}$$

$$\text{Standardized Darwin } (\mathit{StdDarwin}) = \frac{\text{(Actual Darwin (SLP) - Mean Darwin (SLP))}}{\text{Standard Deviation Darwin}}$$

$$\text{Monthly Standard Deviation (MSD)} = \sqrt{\frac{\Sigma(StdTahiti - StdDarwin)^2}{N}}$$

The SOI equation looks as follows:

$$\mathbf{SOI} = \frac{\text{(Standardized Tahiti - Standardized Darwin)}}{MSD} \quad \text{.........\ (6.1)}$$

Detailed calculation of SOI (NOAA) can be found in Appendix J.

ii. Method Used by Australian Bureau of Meteorology: The method used by the Australian Bureau of Meteorology is the Troup SOI [for details see: http://www.bom.gov.au/climate/glossary/soi.shtml], which is the standardized anomaly of the Mean Sea Level Pressure difference between Tahiti and Darwin (Figure 6.5).

Troup SOI is calculated as follows:

$$\text{Troup SOI} = \frac{10^* \text{ [Pdiff- Pdiffav]}}{\text{SD(Pdiff)}} \quad \text{.........(6.2)}$$

Where,

Pdiff = (average Tahiti Mean Sea Level Pressure for the month) – (average Darwin Mean Sea Level Pressure for the month),

Pdiffav = long term average of Pdiff for the month in question, and SD(Pdiff) = long term standard deviation of Pdiff for the month in question.

The multiplication by 10 is a convention. Using this convention, the SOI ranges from about –35 to about +35, and the value of the SOI can be quoted as a whole number. The SOI is usually computed on a monthly basis, with values over longer periods such a year being sometimes us.

The SOI is usually computed on a monthly basis, with values over longer periods such a year being sometimes used. Daily or weekly values of the SOI do not convey much in the way of useful information about the current state of the climate, and accordingly the Bureau of Meteorology does not issue them. Daily values in particular can fluctuate markedly because of daily weather. Detailed calculation of Troupe SOI can be found in Appendix K.

A drawback to this index is that it is based on the pressure at two points and therefore can easily be affected by local weather disturbances making it somewhat noisy when viewed on a month-to-month basis. In order for the index to be more representative of larger scale fluctuations in pressure, it is common to present the SOI averaged over a 5-month period. Generally, the SOI is negative during El Nino, and positive during La Nina.

6.3.2 Sea Surface Temperature Based Indices

Indices based on sea surface temperature, SST (or, its departure from the long-term average) [http://www.pmel.noaa.gov/tao] are computed by taking the average value over some specified region of the ocean. A number of regions in tropical Pacific Ocean have been identified as being important for monitoring and identifying El Nino and La Nina events/indices. The most common ones are referred to as Nino region and are discussed as below (also see Figure 6.7):

1. **Nino 1+2** (0-10S, 80-90W). The region that typically warms first when an El Niño event develops.
2. **Nino 3** (5S-5N; 150W-90W). The region of the tropical Pacific that has the largest variability in sea-surface temperature on El Nino time scales.
3. **Nino 3.4** (5S-5N; 170W-120W). The region that has large variability on El Nino time scales, and that is closer (than Nino3) to the region where changes in local sea-surface temperature are important for shifting the large region of rainfall typically located in the far western Pacific.
4. **Nino 4** (5S-5N: 160E-150W). The region where changes of sea-surface temperature lead to total values around 27.5C, which is thought to be an important threshold in producing rainfall

If the concern regarding El Nino and La Nina is the subsequent effect of that tropical Pacific variability on the climate in a particular region, then one index may be more useful than the others. For widespread global climate variability, Nino 3.4 is generally preferred, because the sea surface temperature variability in this region has the strongest effect on shifting rainfall in the western Pacific. And in turn, shifting the location of rainfall from the western to central Pacific modifies greatly where the location of the heating that drives the majority of the global atmospheric circulation.

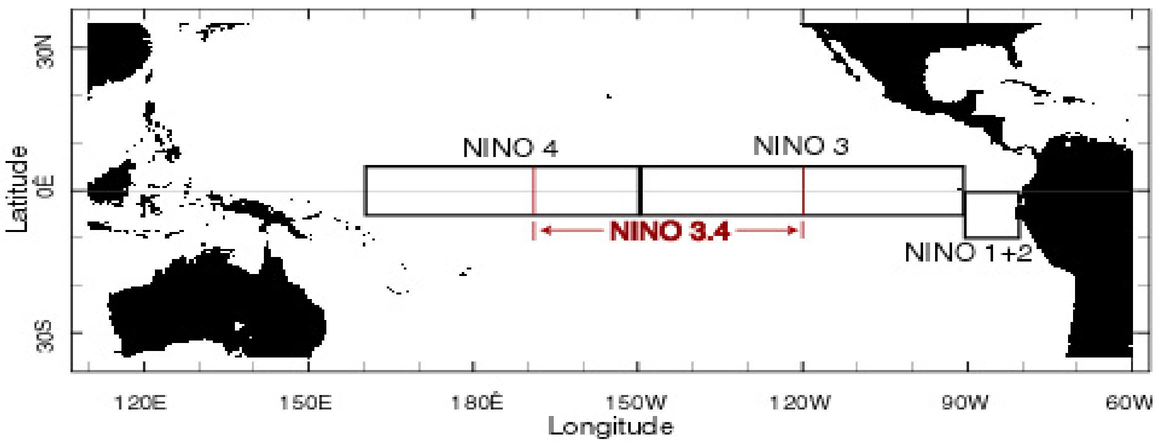


Figure 6.7 SST indices Regions [Source: http://www.pmel.noaa.gov/tao]

In recent decades, indices based on sea surface temperature have come into common usage because satellites and an observing network of buoys in the equatorial Pacific now allow for collection real time, high quality data. The network of buoys referred to is the Tropical Atmosphere Ocean (TAO) Array [http://www.pmel.noaa.gov/tao]. The array consists of a number of moored buoys distributed along the equator that measure both surface conditions in the atmosphere and the surface and subsurface temperatures in the ocean. Figure 6.8 indicates the locations of the moored buoys in the TAO Array.

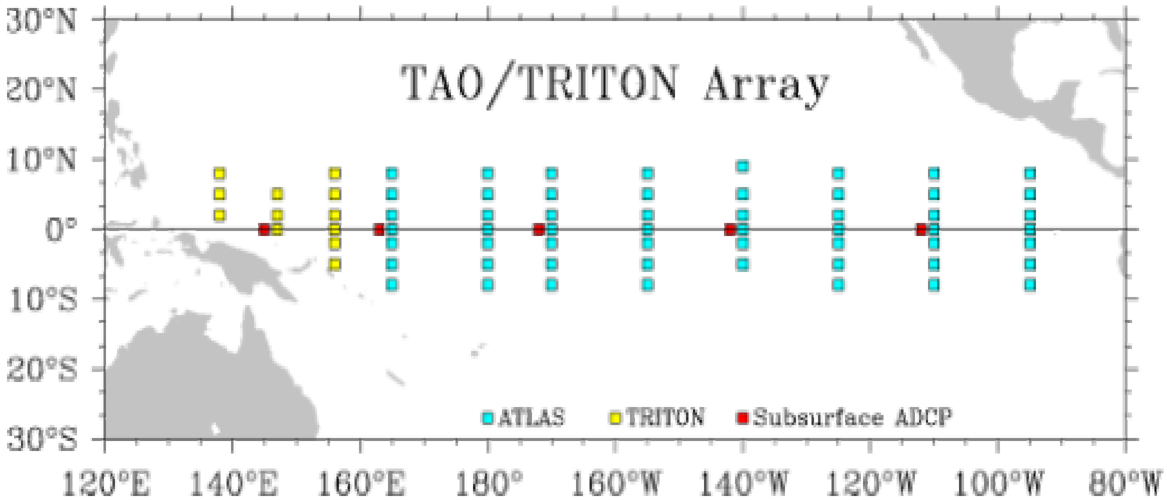


Figure 6.8 TAO Array [Source: http://www.pmel.noaa.gov/tao]

National Oceanic and Atmospheric Administration (NOAA) includes the TAO buoys in the SST analysis, but also include observations from other buoys, ships, and polar orbiting satellites. Data from buoys are the temperature at the depth of about 0.5m. SST observations from ship intakes could be 1m or more. Satellites are measuring radiances from the skin but the SST retrieval algorithms are tuned to buoys, so the resulting SST value better represents the temperature at 0.5m [Email Correspondence with Ms. D. Stokes, NCEP/National Weather Service/NOAA]. Detailed calculation of SST anomalies for Nino 3.4 region is given in Appendix L.

6.4 Identification of El Nino and La Nina year

6.4.1 Based on SOI

In a study of ENSO in the northwest U.S., Redmond used the SOI (equation 6.1) as a predictor for climate, especially during winter [Source: http://www.wrcc.dri.edu/enso/enso.html]. Many El Nino, La Nina categorization approaches use ocean criteria, such as SST, rather than atmospheric criteria, such as the SOI. Most categorizations produce the same years; however, typically a few years are included with one approach that are not included in other, and vice versa). A Six month

(June-November) average of SOI (Equation 6.1) is calculated and the threshold of -1.00 and +1.00 is used to identify the 'strong' El Nino and La Nina years, respectively. Following categories are made depending on the 6-month (June-November) averaged SOI values:

SE - Strongly Negative SOI (-1.00 or less) - "Stronger El Nino"

EN - Mildly Negative SOI (-0.50 or less) - "Moderate El Nino"

N - Neither (SOI between -0.50 and +0.50)- "Neither Nino" or "Nada Nino"

LN - Mildly Positive SOI (+0.50 or more) - "Moderate La Nina"

SL - Strongly Positive SOI (+1.00 or more) - "Stronger La Nina"

Unless stated otherwise, the term "El Nino" based on SOI usually includes EN and SE cases. Unless stated otherwise, the term "La Nina" based on SOI usually includes LN and SL cases (Western Regional Climate Center, 2000). For Example, Table 6.3 shows the calculations for identifying the ENSO years. In Table 6.3, SOI data is obtained from NOAA ftp server (ftp://ftp.ncep.noaa.gov/pub/cpc/wd52dg/data/indices). 6-month average of SOI is calculated and the months and above criterion is used to determine the El Nino and La Nina years based on the 6 month average of SOI.

Table 6.3 ENSO Year Classifications

Year	Ave. NOAA SOI (Eq. 6.1) (June-Nov)	Strong El Nino	Moderate El Nino	Neither Nino	Moderate La Nina	Strong La Nina	RESULTS
1990	-0.27	-	-	N	-	-	**Neutral**
1991	-0.94	-	EN	-	-	-	**El Nino**
1992	-0.79	-	EN	-	-	-	**El Nino**
1993	-1.06	SE	-	-	-	-	**El Nino**
1994	-1.43	SE	-	-	-	-	**El Nino**
1995	0.01	-	-	N	-	-	**Neutral**
1996	0.48	-	-	N	-	-	**Neutral**
1997	-1.65	SE	-	-	-	-	**El Nino**
1998	1.03	-	-	-	-	SL	**La Nina**
1999	0.40	-	-	N	-	-	**Neutral**
2000	0.56	-	-	-	LN	-	**La Nina**
2001	-0.15	-	-	N	-	-	**Neutral**
2002	-0.82	-	EN	-	-	-	**El Nino**

Based upon the definitions presented by Rasmusson and Carpenter [1983] and Ropeleweski and Jones [1987], events in which El Nino or La Nina conditions persisted for multiple years are defined by the first year of individual episode. La Nina events are defined for years that the *SOI remained in the upper 25% of the distribution for 5 months or longer* (Piechota and Dracup, 1996). These years are summarized in the Table 6.4.

Table 6.4 El Nino / La Nina Years Based on Southern Oscillation Index (SOI)

El Nino Year	La Nina Year
1902	1904
1905	1909
1911	1916
1914	1924
1918	1928
1923	1938
1925	1950
1930	1955
1932	1964
1939	1970
1941	1973
1951	1975
1953	1988
1957	1995*
1965	
1969	
1972	
1976	
1982	
1986	
1991	
1994*	
1997*	

*Source: NOAA website

6.4.2 Based on SST

El Nino / La Nina years can be classified using Sea Surface Temperature (SST), where 5 month running means of the SST anomalies for Nino 3.4 region are taken and the months which have the average in excess of *0.4 ^{o}C for six consecutive months* are considered to be El Nino year (Trenberth, 1997). The months where the 5 month running mean is less than *-0.4 ^{o}C for six consecutive months* are classified as La Nina events. This method of classification is shown in Table 6.5.

In Table 6.5, SST data and SST anomaly for Nino 3.4 region is obtained from NOAA ftp server (**ftp://ftp.ncep.noaa.gov/pub/cpc/wd52dg/data/indices**). 5-month running mean of the anomalies is calculated and the months where the 5 month running mean is more than *+0.4 ^{o}C for six consecutive months* are classified as El Nino events. The months where the 5 month running mean is less than *-0.4 ^{o}C for six consecutive months* are classified as La Nina events.

Table 6.5 Classification of El Nino/ La Nina Years based on SST Anomalies in Nino 3.4 region

Year	Month	SST in Nino 3.4 region (^{o}C)	Anomaly (^{o}C)	5 month Running Mean of Anomalies	Classification	
1997	January	25.96	-0.55	-0.40	--	--
1997	February	26.36	-0.33	-0.40	--	--
1997	March	27.03	-0.11	-0.35	--	--
1997	April	28.03	0.34	-0.22	--	--
1997	May	28.6	0.84	0.04	--	--
1997	June	28.94	1.45	0.44	--	--
1997	July	28.92	1.85	0.87	--	--
1997	August	28.84	2.14	1.32	--	--
1997	September	28.93	2.29	1.71	--	--
1997	October	29.23	2.64	2.07	--	--
1997	November	29.32	2.8	2.34	El Nino	--
1997	December	29.26	2.78	2.53	El Nino	--
1998	January	29.1	2.59	2.62	El Nino	--
1998	February	28.86	2.17	2.60	El Nino	--
1998	March	28.67	1.53	2.37	El Nino	--
1998	April	28.56	0.87	1.99	El Nino	--
1998	May	28.47	0.71	1.57	El Nino	--
1998	June	26.72	-0.78	0.90	El Nino	--
1998	July	25.94	-1.14	0.24	--	--

1998	August	25.49	-1.22	-0.31	--	--
1998	September	25.61	-1.04	-0.69	--	--
1998	October	25.34	-1.26	-1.09	--	--
1998	November	25.18	-1.33	-1.20	--	--
1998	December	24.79	-1.69	-1.31	--	--
1999	January	24.9	-1.61	-1.39	--	--
1999	February	25.41	-1.28	-1.43	--	La Nina
1999	March	26.25	-0.89	-1.36	--	La Nina
1999	April	26.84	-0.84	-1.26	--	La Nina
1999	May	26.97	-0.79	-1.08	--	La Nina
1999	June	26.6	-0.9	-0.94	--	La Nina
1999	July	26.35	-0.73	-0.83	--	La Nina
1999	August	25.59	-1.12	-0.88	--	La Nina
1999	September	25.71	-0.94	-0.90	--	La Nina
1999	October	25.64	-0.96	-0.93	--	La Nina
1999	November	25.12	-1.39	-1.03	--	La Nina
1999	December	24.9	-1.57	-1.20	--	La Nina

El Nino /La Nina years, using the *classification given by Trenberth (1997)*, were identified (Table 6.6).

Table 6.6 El Nino/La Nina Years identified after 1950, using Sea Surface Temperatures (SST) for Nino 3.4 region

El Nino Years	La Nina Years
1957-1958	1950-1951
1966	1955-1956
1969-1970	1965
1973	1968
1977	1971-1972
1982-1983	1974-1976
1987-1988	1984-1985
1991 – 1993	1989
1995	1996
1997-1998	1999-2001
2002	

National Oceanic and Atmospheric Administration (NOAA) uses a threshold of *+0.5 °C in Nino 3.4 for a three month average as the minimum value for weak El Nina* *conditions* and *-0.5 °C in Nino 4 for La Nina* (Email correspondence with Mr. M. Halpert, CPC, NOAA).

In order to show the anomalies in SST in various Nino regions, monthly SST data from January 1996 to December 1998 has been compiled and listed in Table 6.7. The SST data was obtained from Climate Prediction Center (CPC) website [http://www.cpc.ncep.noaa.gov/data/indices/]. In Table 6.7, the anomalies in the Sea Surface temperatures in the corresponding Nino region show the effect of ENSO events. The table shows the SST pattern for years 1996, 1997 and 1998 that are identified as Neutral, El Nino and La Nina Event years, respectively. For Example, Nino 3.4 region (Column 9 and 10) clearly shows the increase in the sea surface temperature from the normal in the last six months (marked red in the Table 6.7) of 1997 whereas last six months of 1998 (marked blue in the Table 6.7) show decrease in the sea surface temperatures.

Table 6.7 Monthly SST and Anomalies (^{o} C) for 1996-1998, for different Nino regions

(source: **http://www.cpc.ncep.noaa.gov/data/indices/**)

1	2	3	4	5	6	7	8	9	10
Year	Month	Nino 1+2	Anomaly	Nino 3	Anomaly	Nino 4	Anomaly	Nino 3.4	Anomaly
1996	Jan	23.84	-0.58	24.96	-0.65	27.92	-0.22	25.74	-0.77
1996	Feb	25.71	-0.26	25.72	-0.64	27.57	-0.43	25.85	-0.85
1996	Mar	26.09	-0.28	26.71	-0.38	27.71	-0.38	26.62	-0.52
1996	Apr	23.85	-1.49	26.72	-0.68	28.07	-0.34	27.36	-0.32
1996	May	22.89	-1.35	26.33	-0.73	28.43	-0.22	27.37	-0.39
1996	June	21.56	-1.4	25.89	-0.49	28.55	-0.09	27.32	-0.17
1996	Jul	20.02	-1.77	25.35	-0.23	28.5	-0.08	27.09	0.01
1996	Aug	19.53	-1.25	24.6	-0.35	28.54	0.09	26.56	-0.14
1996	Sept	19.24	-1.2	24.37	-0.46	28.43	-0.06	26.35	-0.3
1996	Oct	19.95	-0.93	24.37	-0.52	28.42	0.01	26.24	-0.36
1996	Nov	20.26	-1.38	24.38	-0.57	28.33	-0.03	26.19	-0.32
1996	Dec	21.61	-1.18	24.2	-0.88	28.44	0.16	26.02	-0.45
1997	Jan	23.67	-0.75	24.7	-0.91	28.41	0.27	25.96	-0.55
1997	Feb	25.74	-0.23	25.75	-0.61	28.33	0.32	26.36	-0.33
1997	Mar	26.95	0.59	26.98	-0.11	28.52	0.43	27.03	-0.11
1997	Apr	26.64	1.3	27.59	0.18	29.32	0.91	28.03	0.34
1997	May	26.71	2.47	28.06	1	29.45	0.81	28.6	0.84
1997	June	26.27	3.31	28.14	1.76	29.4	0.76	28.94	1.45
1997	Jul	25.59	3.79	28.01	2.43	29.5	0.92	28.92	1.85
1997	Aug	24.8	4.01	27.84	2.89	29.26	0.8	28.84	2.14
1997	Sept	24.4	3.96	27.84	3.01	29.32	0.84	28.93	2.29
1997	Oct	24.58	3.69	28.17	3.29	29.32	0.91	29.23	2.64
1997	Nov	25.63	3.99	28.55	3.59	29.49	1.13	29.32	2.8
1997	Dec	26.92	4.13	28.76	3.68	29.32	1.04	29.26	2.78
1998	Jan	28.22	3.8	28.94	3.32	29.01	0.87	29.1	2.59
1998	Feb	28.98	3.01	28.93	2.57	28.87	0.86	28.86	2.17
1998	Mar	29.15	2.79	29.14	2.05	28.65	0.56	28.67	1.53
1998	Apr	28.61	3.28	29.09	1.68	28.53	0.13	28.56	0.87
1998	May	27.69	3.45	28.17	1.11	28.71	0.06	28.47	0.71
1998	June	25.18	2.22	26	-0.37	28.61	-0.03	26.72	-0.78
1998	Jul	23.43	1.63	25.24	-0.35	28.07	-0.5	25.94	-1.14
1998	Aug	21.77	0.98	24.63	-0.33	27.77	-0.68	25.49	-1.22
1998	Sept	20.87	0.43	24.19	-0.64	27.88	-0.6	25.61	-1.04
1998	Oct	21.16	0.27	24.06	-0.83	27.33	-1.07	25.34	-1.26
1998	Nov	21.43	-0.21	24.11	-0.85	27.23	-1.13	25.18	-1.33
1998	Dec	22.56	-0.24	23.86	-1.22	27.11	-1.17	24.79	-1.69

The difference in the methods of classification of El Nino/ La Nina/ Neutral years can be seen in Table 6.2. This difference makes it more difficult to correctly identify these years and hence study the effects of ENSO events on the streamflow or precipitation. El Nino/ La Nina years identified in the studies by Piechota et al (1996) are used to maintain the consistency through out the study.

El Nino/La Nina years classified using SOI (Table 6.3) and SST Anomalies (Table 6.7) does not match exactly but similar trend in SST for most of the years can be seen. For the years where the classification matches for the two methods, increase in sea surface temperatures from the normal is seen during the El Nino years and a significant decrease in sea surface temperatures in for the Nino 3.4 region are observed for La Nina (Column 10 in Table 6.7).

7. Analysis and Results

7.1 Introduction

Chapter 6 described ENSO events, ENSO indices and classification of ENSO years in detail. According to various studies ENSO events are observed to be causing climate changes across the globe (for details see Chapter 6). El Nino events cause heavy rainfall in the northern Peru and Ecuador and droughts in Australia, Indonesia and northeastern Brazil. In order to test the ENSO impacts as reported in the literature historical data of streamflow and precipitation in various parts of the world are analyzed with respect to ENSO events. The objective of the chapter is to study and identify the pattern in the change of streamflow and precipitation based upon ENSO events.

Section 7.2.1 and 7.2.2 describe the study regions and data sources, respectively. The methods for analysis are discussed in section 7.2.3. Section 7.2.3 includes the results of various analysis and inferences from the results are discussed in section 7.3.

7.2 Analysis of ENSO Impacts on Streamflows in different Geographic Regions

7.2.1 Classification of Data

The effects of El Nino and La Nina years on the on the streamflow / precipitation across the world were studied. The whole data is divided in four categories namely: El Nino, La Nina, Neutral years and Whole dataset. *El Nino* and *La Nina datasets* consisted of the dataset for the El Nino and La Nina years identified, respectively. *Neutral year dataset* was the dataset for all the years excluding El Nino and La Nina years. *Whole dataset* was the term given to the original dataset without any exclusion. El Nino and La Nina years since 1900 were identified based on a study by Piechota and Dracup (1996) (see section 6.4.1). 23 El Nino, 14 La Nina and 65 Neutral years were considered based upon the SOI (Table 6.4) for the analyses.

7.2.2 Study Regions

Streamflow records from four rivers and precipitation dataset another region are chosen to identify the effects of El Nino/ La Nina events on streamflow and precipitation. The regions are chosen to study the effects of El Nino/ La Nina Events across the globe. Due to non-availability of appropriate data for any river in Asian subcontinent, precipitation data for Chennai station in India is chosen to study the effects of ENSO on Indian climate.

The regions chosen are shown in Figure 7.1 and are listed, as follows:

1. Murray River at Australia: Murray River is a river of Australia. Tacumwal, located 275kms from Melbourne, is situated at the border of New South Wales and Victoria.

2. Rio Zana at Peru (South America): Rio Zana streamgage at El Batan (latitude 6.08^{o}S, longitude 79.30^{o}W, Elevation 250 m) is located at the southwest coast of Peru.

3. River Jamari at Brazil (South America): River Jamari streamgage at Ariquemes (latitude 9.93^{o}S, longitude 63.07^{o}W, Drainage area 7295 km^{2}) is located in southwest Brazil.

4. Chennai (India): Chennai is one of the metropolitan cities of India. It is located in eastern coast of India in Bay of Bengal.

5. Rappahanock River at Virginia, USA (North America): Rappahannock river streamflow data is obtained from the streamgage situated at Fredericksburg which is located close to Washington D.C.

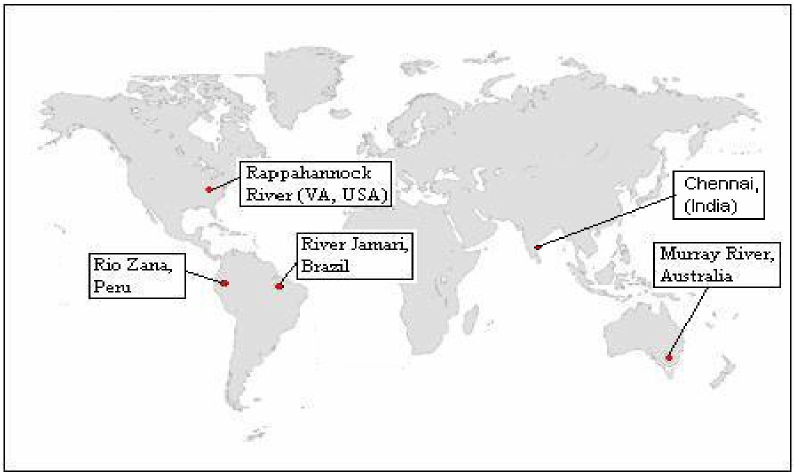


Figure 7.1 Study Regions for Effect of El Nino/ La Nina Events on Streamflows

7.2.3 Data Sources

A brief description of the data sources is given below:

1. **SOI** : Mean Monthly SOI data is obtained from National Oceanic and Atmospheric Administration (NOAA) website (http://www.cpc.ncep.noaa.gov/data/indices/). SOI values (equation 6.1) are available from 1882 till date. The complete data is given in Appendix J.

2. **Murray River at Australia:** Mean monthly streamflow data for Murray River at Tocumwal is obtained from Commonwealth Beurau of Meterology (http://www.bom.gov.au). Data from 1933 to 2001 was used in the analyses. The complete data is given in Appendix F.

3. **Rio Zana at Peru:** Mean monthly streamflow data for Rio Zana at Peru is obtained from Center for study of Hydroclimatology in the Pacific Rim (http://www.seas.ucla.edu/chpr/peru/peru.htm). Data from 1933 to 1992 was used in the analyses. The complete data is given in Appendix G.

4. **River Jamari at Brazil:** Mean monthly streamflow data for River Jamari at Brazil is obtained from Center for Sustainibility and Global Environment

(http://www.sage.wisc.edu:16080/download/LBA/macrohydro/). Data from 1972 to 1997 is used in the analyses. The complete data is given in Appendix H.

5. **Chennai (India) Precipitation:** Monthly precipitation data for Chennai (India) is obtained from Data Support Section (DSS) at University Corporation for Atmospheric Research (UCAR) (http://dss.ucar.edu/datasets/ds570.0/data/) Data from 1933 to 1998 is used in the analyses. The complete data is given in Appendix I.

6. **Rappahannock River at Virginia, USA**: Mean monthly streamflow data for Rappahannock River at Virginia (USA) is obtained from U.S. Geological Survey (USGS) website (http://waterdata.usgs.gov/va/nwis/rt). Data from 1933 to 2001 is used in the analyses. The complete data is given in Appendix A

7.2.4 Methods and Results

A. Lag Correlation Analysis

Lag correlation analysis is done to establish and analyze the dependence of streamflow on SOI. A correlation coefficient value of 0.3 or above is considered significant. This assumption is consistent with the earlier studies by Chiew et al (1998).

Equation 7.1 is used to calculate the correlation at lag 'k' between SOI and streamflow timeseries. 'Lag' is difference in months between which the dependence is being analyzed. For example, if the dependence between the January SOI and February Streamflow is being analyzed, the lag is said to be 1 and so on.

The stepwise method for Lag correlation analyses is given below.

Step 1: Take SOI and streamflow data for any period. The data should be continuous for both the series during that period.

Step 2: Use equation 7.1 to compute correlation coefficients at various lags.

$$C_{zx}(k) = \sum_{t=1}^{n-k} (Z_t - \overline{Z})(X_{t+k} - \overline{X}) / N$$

$$R_{zx}(k) = C_{zx}(k)/(S_Z * S_X) \quad \text{..............................7.1}$$

Where, X_t : SOI timeseries

Z_t : Streamflow timeseries

N : Total number of data points

S_Z : Standard Deviation of series "Z"

S_X : Standard Deviation of series "X"

$C_{ZX}(k)$: Covariance of lag "k"

$R_{ZX}(k)$: Correlation Coefficient

Table 7.1 shows a set of calculations. Column 1 is the year of the timeseries. Column 2 is the downloaded mean monthly SOI values for January month. Column 4 is the downloaded mean monthly flow values for Rappahannock River at Fredericksburg gage for February, for which relation between SOI and streamflow during El Nino years is desired. Only the years with the El Nino events are considered in this particular example. Subtracting each term with the average of the series and dividing by the standard deviation of the series, in Columns 3 and 5 respectively standardize SOI and streamflows. Further, in Column 6 correlation equation (equation 7.1) is used to find the correlation coefficient for the two series for Lag 1 (correlation of January SOI with February Mean monthly streamflows).

Table 7.1 Sample Calculation Table for SOI-Streamflow Lag Correlation

1	2	3	4	5	6
Year	SOI	Standardized SOI	Mean Monthly Streamflow (cfs)	Standardized Mean Monthly Streamflow (cfs)	Col3 * Col5
1911	0.20	-0.30	2350	0.27	-0.082
1914	-0.70	-0.91	2794	0.67	-0.604
1918	1.80	0.78	1200	-0.74	-0.582
1923	0.60	-0.03	1480	-0.50	0.014
1925	0.60	-0.03	3623	1.40	-0.040
1930	1.50	0.58	1206	-0.74	-0.428
1932	0.00	-0.43	1205	-0.74	0.321
1939	2.10	0.99	1676	-0.32	-0.318
1941	-1.40	-1.38	2246	0.18	-0.250

1951	2.70	1.39	1343	-0.62	-0.859
1953	0.40	-0.16	3412	1.21	-0.198
1957	1.00	0.24	1257	-0.69	-0.168
1965	-1.10	-1.18	1927	-0.10	0.119
1969	-3.20	-2.60	1057	-0.87	2.261
1972	0.60	-0.03	1229	-0.72	0.020
1976	2.40	1.19	4674	2.33	2.766
1982	2.20	1.05	1008	-0.91	-0.962
1986	1.50	0.58	1114	-0.82	-0.476
1991	1.00	0.24	3988	1.72	0.416
Average =	0.64		2041.53	Covariance =	0.050
Std. Dev. =	1.48		1131.14	Correlation =	0.050

The analysis is done for the El Nino Years, La Nina years and neutral years to find the correlation between the Streamflows and SOI during ENSO events.

Results

Lag Correlation analysis identifies the relation between the two series for certain 'Lag'. Analysis was done for El Nino years/ La Nina Years/ Neutral Years identified by the SOI (Piechota et al, 1996). The correlation coefficients obtained by the analyses are plotted against the 'beginning' month (see Figures 7.2 a, b, and c). 'Beginning' month denotes the starting month in the SOI series. For example, beginning month 2 means that monthly SOI series for February is considered for analysis along with the other series (streamflow/ precipitation) that is lagged by a chosen lag (i.e. March monthly series for streamflow/ precipitation is taken for Lag of 1). For example, Figure 7.2 a shows variation in the values of correlation coefficient between SOI time series and streamflow data for Rio Zana for time lag varying from zero to eleven months, for El Nino years.

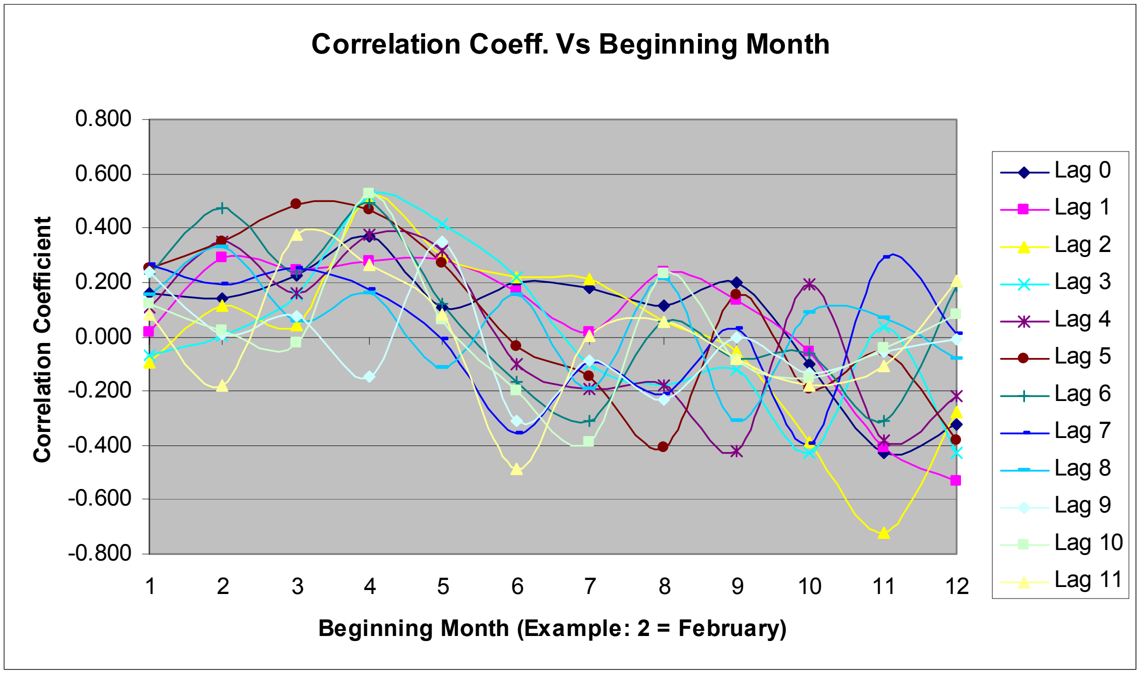


Figure 7.2 a. Plots of Correlation coefficients for El Nino Years for Rio Zana streamflows in Peru

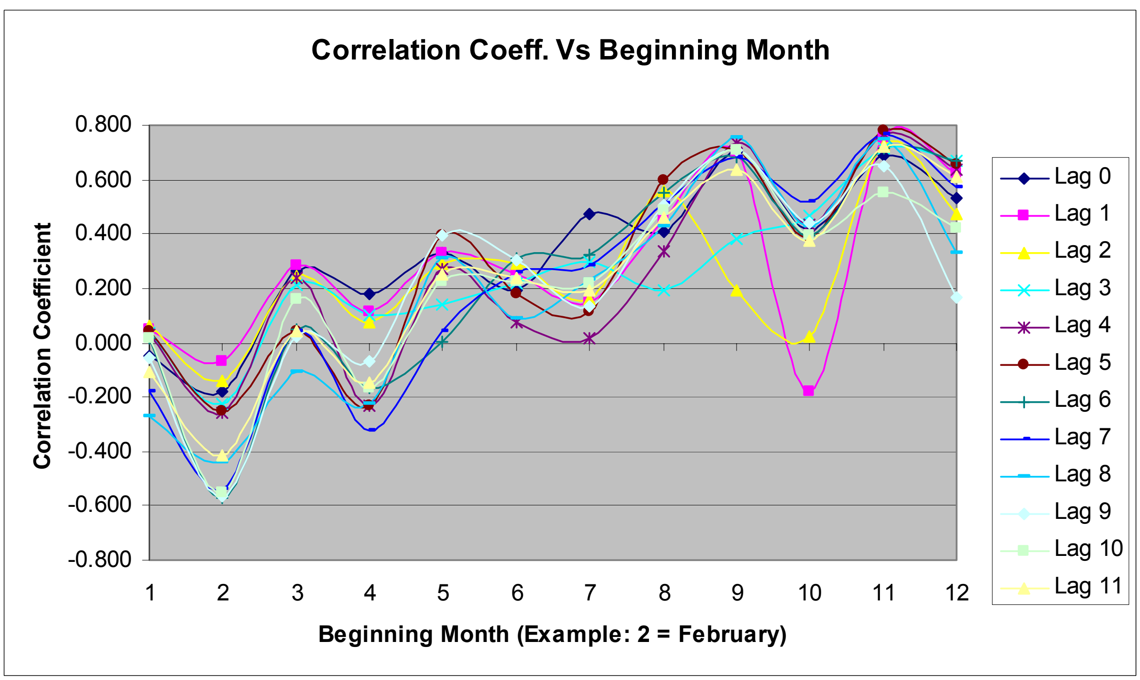


Figure 7.2 b Plots of Correlation coefficients for La Nina Years for River Jamari streamflows in Brazil

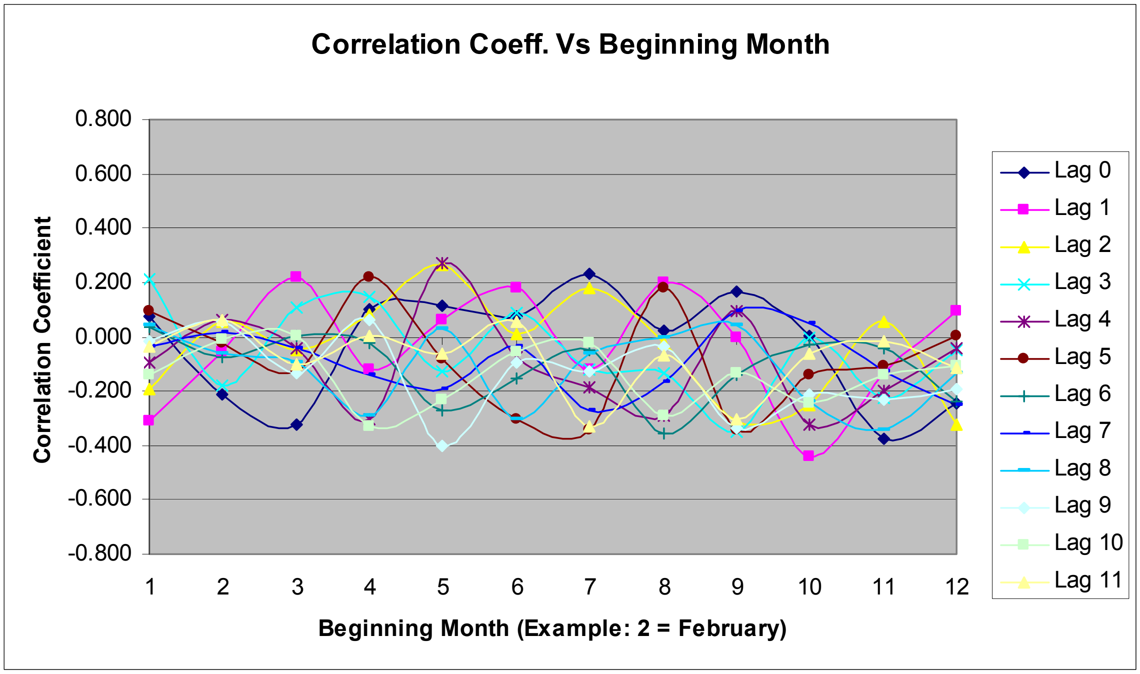


Figure 7.2 c Plots of Correlation coefficients for Neutral Years for Chennai Precipitation in India

In the lag-correlation plots, a significant correlation (+/- 0.3) is observed for El Nino/ La Nina years for some lags (for example, Figure 7.2 a, b and c) but no significant correlation can be spotted for neutral years for any Lag. It also shows that streamflows/ precipitation are correlated to the SOI for the El Nino/ La Nina period but no inferences can be made from the results for neutral years.

Though the results and plots from lag correlation analyses show some significant values for particular lag but since the values do not show any consistent behavior, no inferences can be made (see detailed results in Appendix L). Since Lag correlation analysis did not yield meaningful results, it was considered to carry out simple statistical analysis of the data classified according to El Nino, La Nina, and Neutral years. The objective is to observe differences in central tendencies of the streamflow/ precipitation data classified in section 7.2.4 B.

B. Descriptive Statistics

Simple statistical analysis was carried out on datasets (SOI, River Murray streamflows, River Jamari streamflows, Rappahannock River streamflows, Rio Zana streamflows, and Chennai precipitation) for El Nino, La Nina and Neutral years using following steps. The stepwise procedure is given below:

Step 1: From the datasets three different groups for series were made for whole dataset, El Nino, and La Nina years.
Step 2: Means of each series are calculated.
Step 3: Mean values of SOI and streamflow/ precipitation series were compared to identify a pattern between the mean values for SOI and streamflow/ precipitation series.

Furthermore, For example, Table 7.2 shows the descriptive statistics of streamgage for Rappahannock River at Fredericksburg. Mean, standard deviation, minimum and maximum for the mean monthly streamflow series is calculated for El Nino years. These values are compared to SOI dataset.

Table 7.2 Descriptive Statistics of Streamflows for Rappahannock River at Fredericksburg for El NinoYears

Year	Jan	Feb	March	April	May	June	July	August	Sept	Oct	Nov	Dec
1911	2350.00	1479.00	1249.00	1813.00	652.00	571.00	237.00	562.00	1212.00	968.00	1209.00	2032.00
1914	2794.00	2324.00	2495.00	2535.00	1139.00	523.00	515.00	275.00	163.00	386.00	675.00	1502.00
1918	1200.00	5195.00	2325.00	7155.00	1494.00	1180.00	573.00	1124.00	1025.00	309.00	635.00	2046.00
1923	1480.00	1477.00	3016.00	1932.00	1056.00	745.00	575.00	1785.00	1481.00	576.00	663.00	1611.00
1925	3623.00	4079.00	1569.00	1167.00	1259.00	589.00	389.00	226.00	155.00	277.00	755.00	1544.00
1930	1206.00	2340.00	1750.00	1569.00	601.00	344.00	78.60	21.10	46.50	15.30	75.40	147.00
1932	1205.00	1159.00	2435.00	1639.00	3164.00	588.00	358.00	134.00	58.10	1477.00	4924.00	1949.00
1939	1676.00	4241.00	2594.00	1844.00	953.00	562.00	2056.00	1348.00	320.00	290.00	662.00	476.00
1941	2246.00	1276.00	1625.00	2457.00	666.00	651.00	2030.00	620.00	255.00	133.00	213.00	667.00
1951	1343.00	3272.00	3210.00	3610.00	1247.00	3182.00	828.00	503.00	221.00	181.00	634.00	2126.00
1953	3412.00	2101.00	4638.00	2740.00	2167.00	1130.00	344.00	259.00	116.00	123.00	247.00	867.00
1957	1257.00	2788.00	2585.00	2733.00	926.00	729.00	167.00	60.00	229.00	631.00	816.00	2728.00
1965	1927.00	3715.00	3347.00	1285.00	880.00	405.00	261.00	192.00	156.00	277.00	204.00	205.00
1969	2485.00	3058.00	1637.00	2922.00	1382.00	521.00	774.00	421.00	171.00	315.00	3303.00	1654.00
1972	1229.00	4542.00	2422.00	2268.00	2841.00	7112.00	1948.00	877.00	338.00	2863.00	4538.00	4947.00
1976	4674.00	2068.00	1611.00	2200.00	1064.00	1397.00	638.00	300.00	346.00	5466.00	1343.00	1797.00
1982	1008.00	4217.00	2382.00	1499.00	1290.00	3584.00	803.00	909.00	260.00	334.00	651.00	1266.00
1986	1114.00	2191.00	1993.00	1572.00	751.00	293.00	276.00	227.00	183.00	120.00	391.00	1535.00
1991	3988.00	1192.00	2589.00	1805.00	1011.00	771.00	679.00	270.00	151.00	137.00	277.00	1238.00
1994	3185.00	4418.00	7413.00	2587.00	1116.00	536.00	1652.00	2182.00	592.00	398.00	518.00	897.00
1997	2336.00	2537.00	3348.00	1867.00	979.00	1081.00	824.00	237.00	383.00	348.00	2740.00	842.00
Descriptive Analysis												
Mean	2178.00	2841.38	2677.76	2342.81	1268.48	1261.62	762.17	596.77	374.36	744.01	1213.02	1527.43
Std.Dev.	1078.45	1248.97	1339.45	1258.17	672.27	1589.88	620.72	583.02	388.38	1252.38	1415.49	1030.70
Min	1008.00	1159.00	1249.00	1167.00	601.00	293.00	78.60	21.10	46.50	15.30	75.40	147.00
Max	4674.00	5195.00	7413.00	7155.00	3164.00	7112.00	2056.00	2182.00	1481.00	5466.00	4924.00	4947.00

Results

To analyze the changes in the streamflow/ precipitation with the El Nino/ La Nina year, the anomalies (deviation from the normal) were calculated by subtracting the means from the values for a particular month. For example, Table 7.3 shows the average values of January month series for all the datasets. For example, 0.56 cubic m/sec is the mean of mean monthly streamflow anomaly for January month series for Rio Zana River for El Nino years. A comparison was made between these values for all the datasets to identify a pattern in streamflow and precipitation for all the datasets with ENSO events. Detailed results can be found in Appendix M.

From the descriptive analysis of streamflows, average values of the mean monthly streamflow anomalies for Rio Zana and River Jamari show greater values in El Nino years than La Nina years, while Murray River show opposite trend as shown in the Table 7.3. This shows the 'see-saw' of the climate in Western and Eastern Pacific regions. Rappahannock River does not show any consistent pattern for the same analyses. The difference between the El Nino Years and La Nina Series does not show in the mean of streamflow series for Rappahannock River.

Table 7.3 Means of Average Monthly Streamflow Anomaly of Rivers, for El Nino, La Nina Years (For January series)

	January		
Dataset	El Nino years	Mean of Monthly timeseries for Whole Dataset	La Nina years
Rio Zana, Peru (cubic m/sec)	0.56	5.65	-0.18
River Jamari, Brazil (cubic m/sec)	3.60	272.52	-33.85
Murray River, Australia (cubic m/sec)	-240.29	9679.00	-490.11

Rappahannock River, Virginia USA (cfs)	-456.11	2226.65	597.20
Chennai Precipitation, India (tenths of mm)	-158.94	246.57	-57.72

The results for descriptive analyses are shown in Figure 7.3 a, b, c, d, e and f, where the mean monthly streamflows/precipitation values are plotted against each month for El Nino/La Nina/ Neutral years and whole data set. As expected, the mean monthly SOI values are negative for El Nino years while positive for La Nina years. SOI values remain close to zero for neutral year and whole dataset. Detailed results can be found in Appendix N.

While the rivers of Peru and Brazil show greater flows than normal (mean of whole dataset) for El Nino years and lower than normal (mean of whole dataset) for La Nina Years, Australian River (Murray River) shows opposite trend which further establishes the 'see-saw' of the climate in eastern and western pacific regions. No particular trend can be spotted for precipitation in India and streamflow of Rappahannock river.

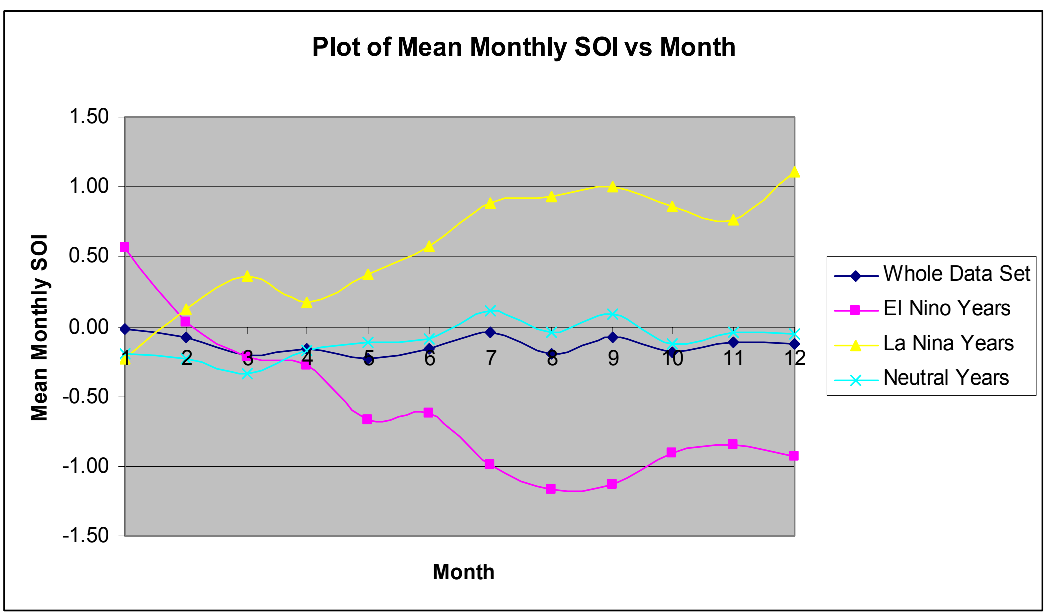


Figure 7.3 a

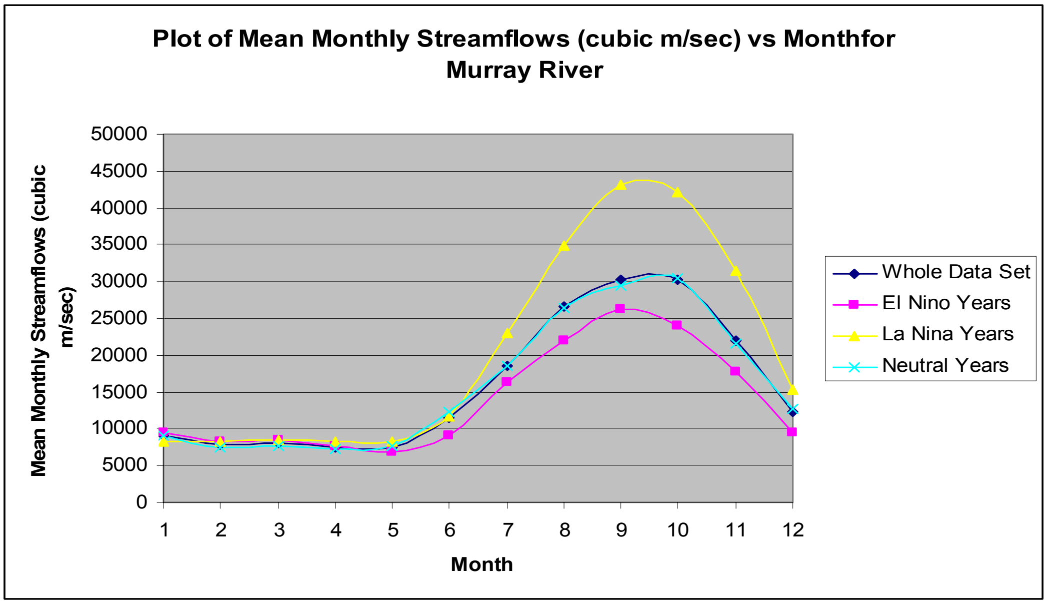


Figure 7.3 b.

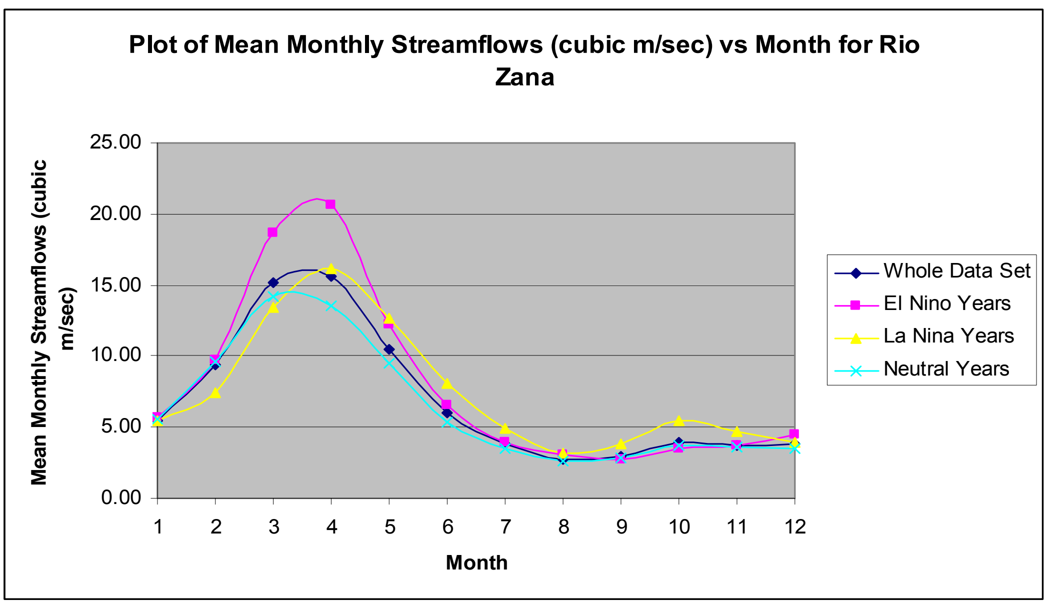


Figure 7.3 c

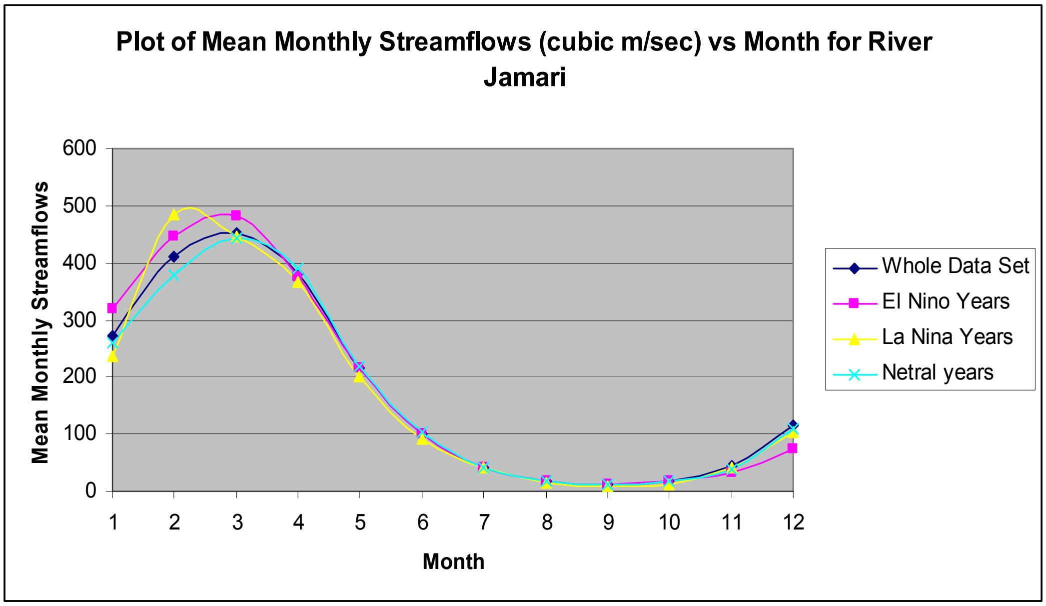


Figure 7.3 d

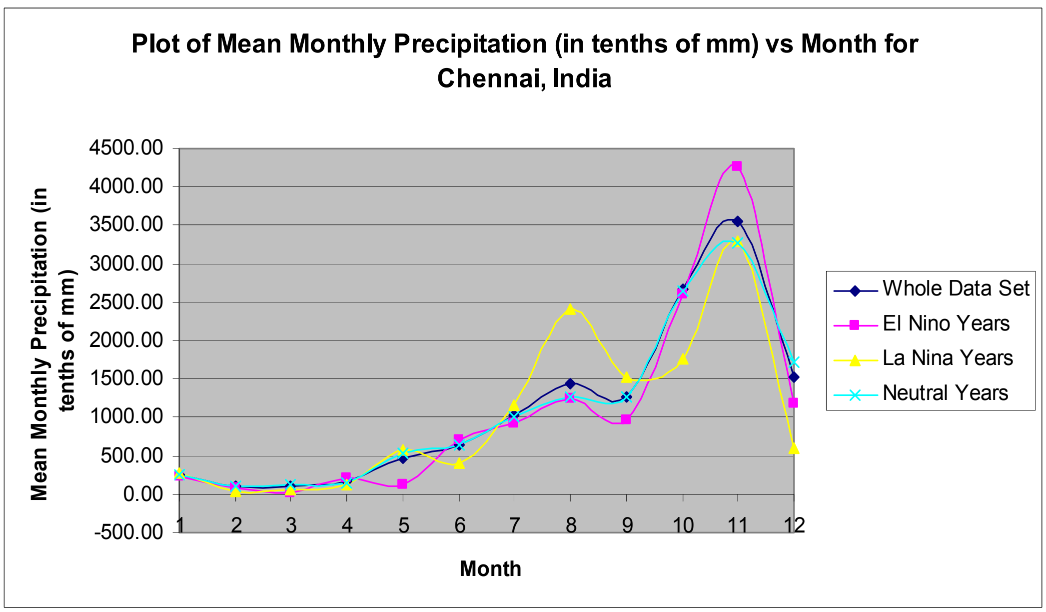


Figure 7.3 e

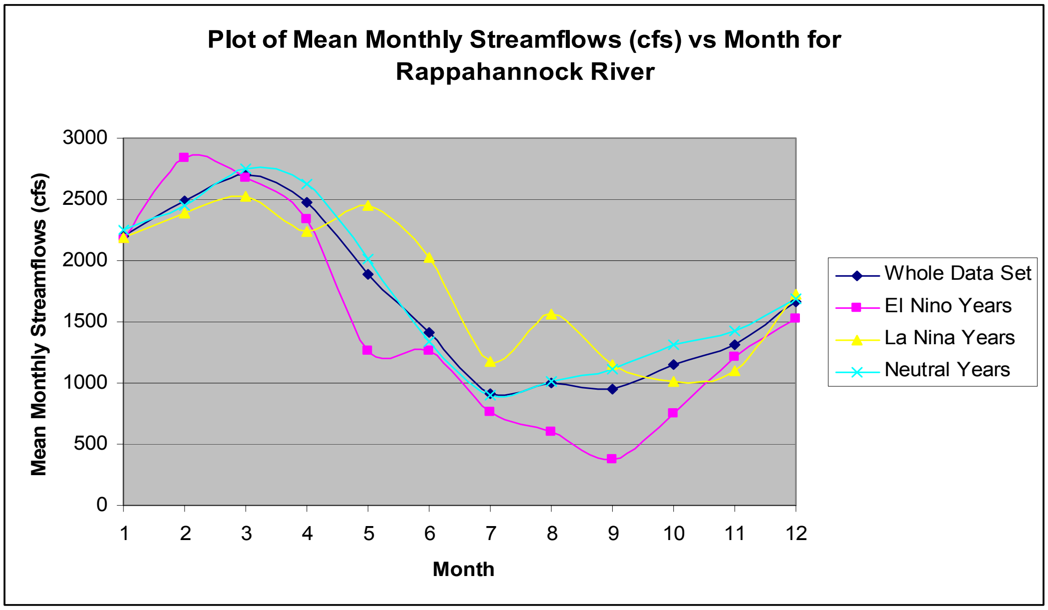


Figure 7.3 f

Figure 7.3 Plots of Monthly Means for El Nino/ La Nina Years for a. SOI, b. Murray River Streamflows, c. Rio Zana Streamflows, d. River Jamari Streamflows, e. Chennai Precipitation and f. Rappahannock River Streamflows

Mean monthly streamflow anomalies (deviation from the mean) (Figure 7.4 a, b, c, d, e and f) were plotted against corresponding months to identify the pattern in the deviation from the normal for El Nino/ La Nina Years. Figure 7.4 a shows that the SOI values for El Nino years are less than mean whereas they show the opposite trend for La Nina years. Figure 7.4 b shows a decrease in streamflows in Australian River for El Nino years and increase during La Nina years. All the other datasets fail to show any particular pattern in the deviation from the normal during El Nino/ La Nina years.

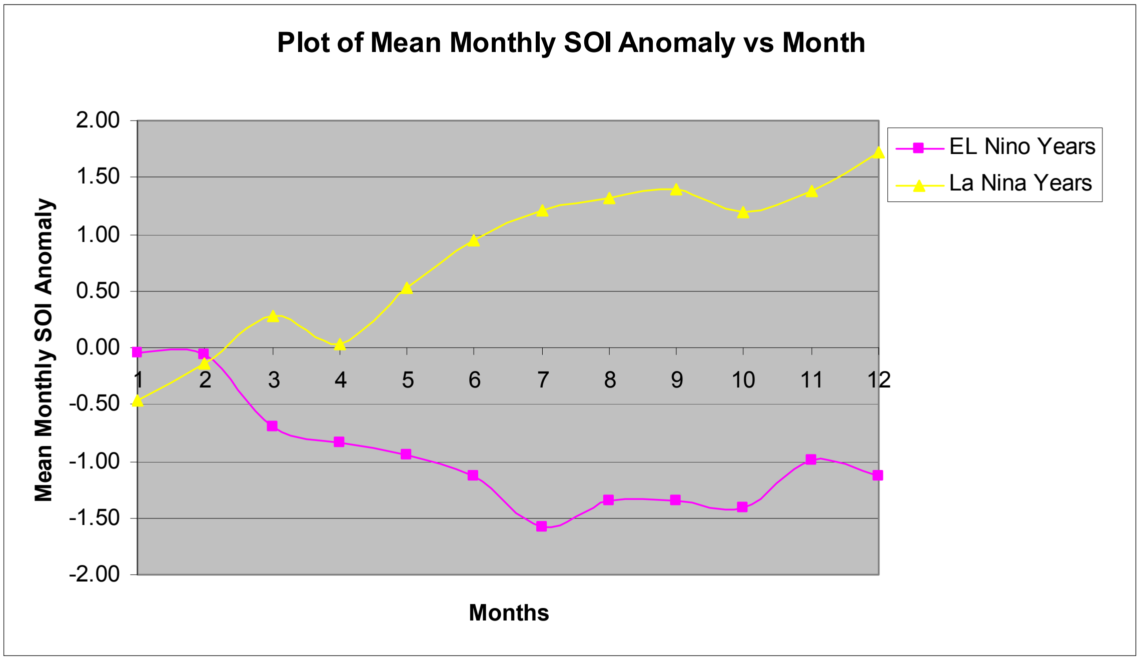


Figure 7.4 a

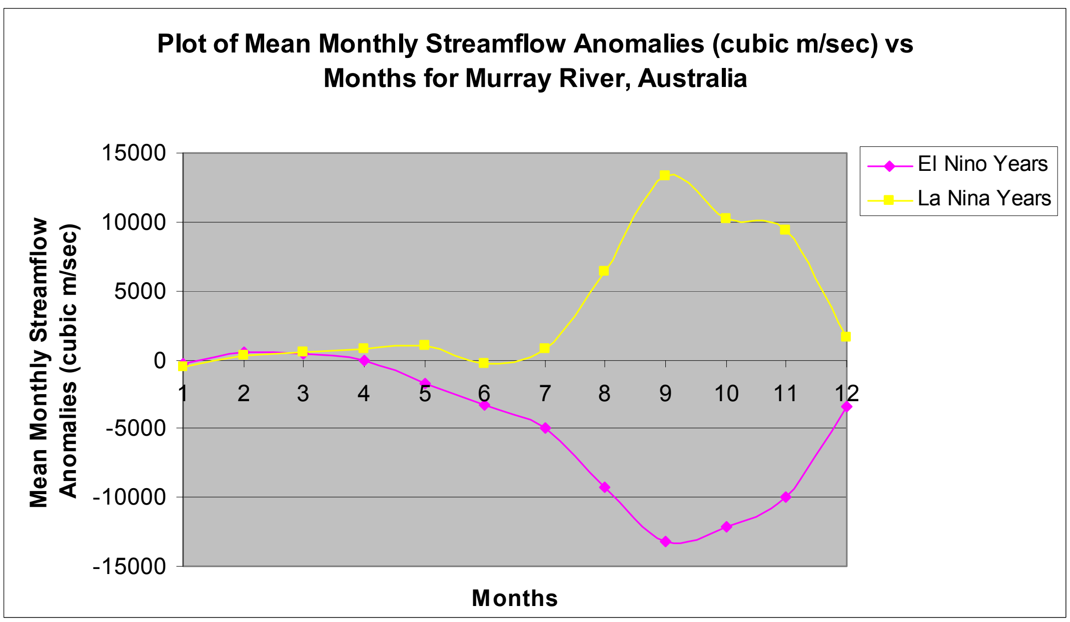


Figure 7.4 b

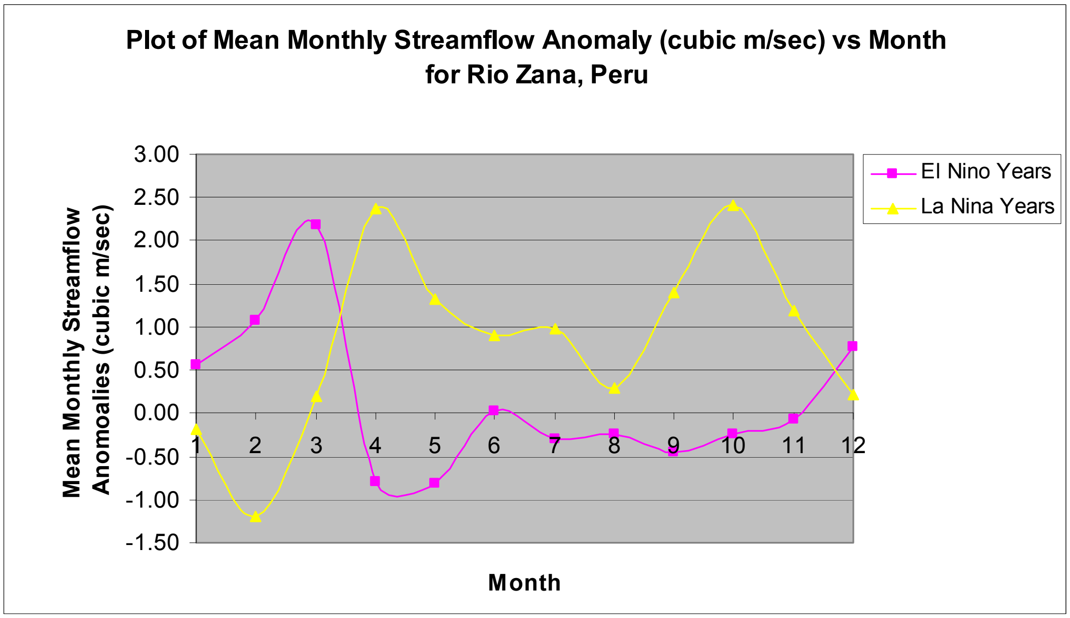
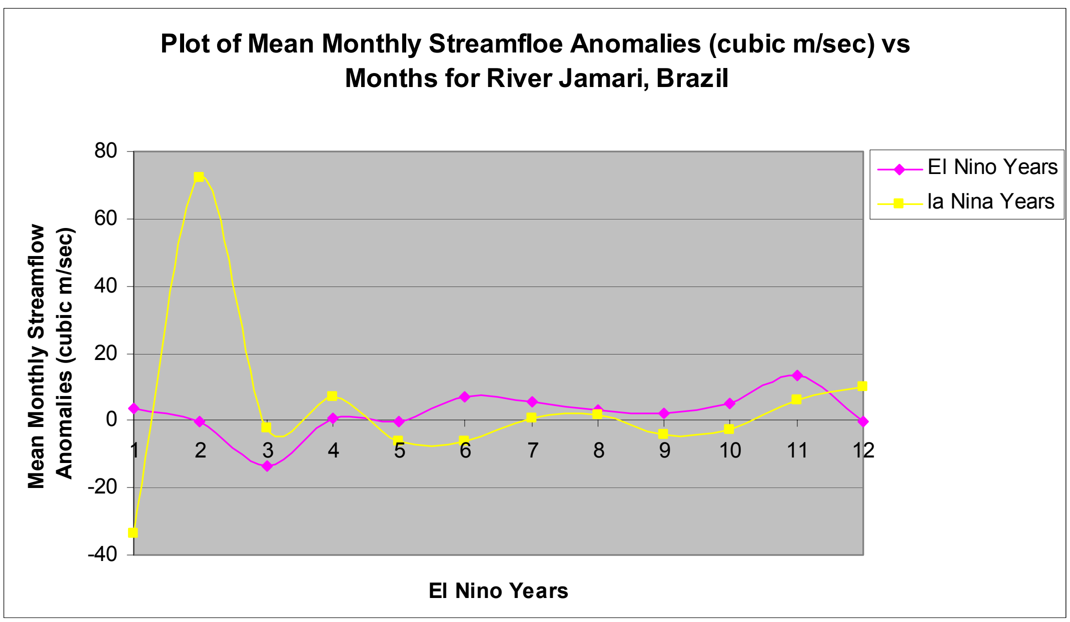


Figure 7.4 c



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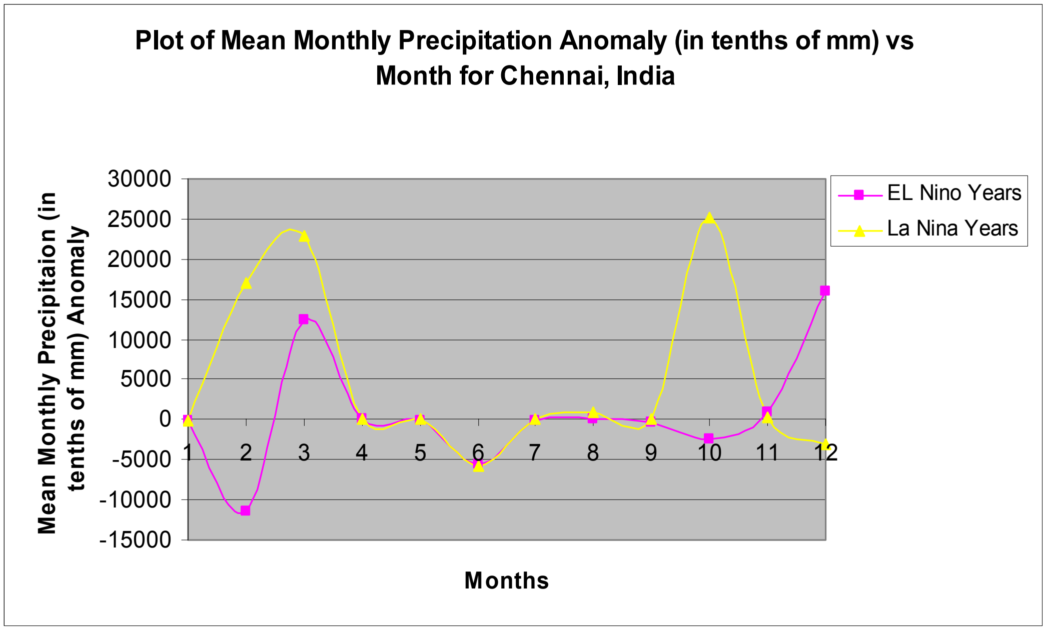

Figure 7.4 e

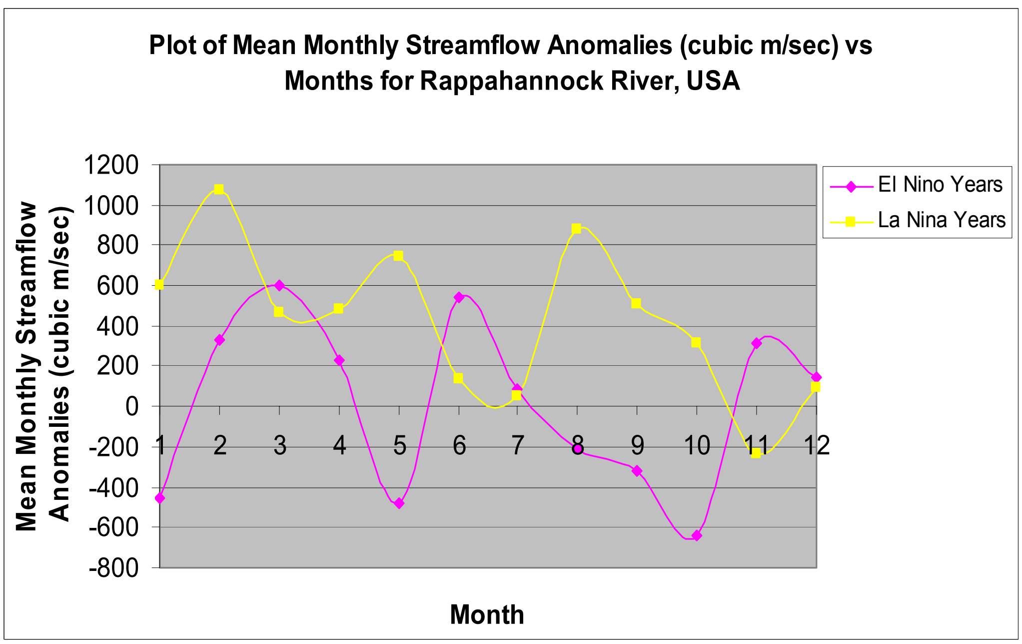

Figure 7.4 f

Figure 7.4 Plots of Mean Monthly Anomalies for El Nino/ La Nina Years for a. SOI, b. Murray River Streamflows, c. Rio Zana Streamflows, d. River Jamari Streamflows, e. Chennai Precipitation and f. Rappahannock River Streamflows

8. Conclusions

8.1 Lag correlation

Lag correlation analysis between the SOI and the flows and precipitation does not show any significant pattern for El Nino, La Nina or Neutral years. This can be attributed to the fact that there exist so many methods to identify the ENSO years. Past studies have come up with different methods based on SOI and SST (for details see section 6.4) but all of them fail to agree on in most of the cases. Furthermore, number of ENSO events (23 El Nino, 14 La Nina) might also be too less to identify any pattern. Hence, less number of representative events might also be one of the big factors in not getting a significant pattern based on the lag correlation analysis.

8.2 Descriptive Statistics

Descriptive analysis shows a definite increase in the streamflows for the Peru streamflows for most of the months during El Nino/La Nina years and decrease for the Australian River. This shows a 'see-saw' of climate in Western Pacific Regions (Australia) and Eastern Pacific Regions (Peru).

Using the same analyses, Precipitation in Chennai, India, stream flows in Brazilian River and streamflow for Rappahnnock River, Virginia (USA) River does not show any definite trend for El Nino / La Nina Years. For some months, the streamflows show an increase in streamflows but for others they show a decrease, making it impossible to identify any pattern. From this analysis it may be concluded that El Nino/ La Nina events does not affect the climate of corresponding region of USA.

According to the various studies on the global climate, the El Nino was found to be causing increases rainfall in Peru region while droughts in the western Pacific region (Australia) (http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html). This study confirms this effect as seen in the descriptive analysis plots (Figure 7.3 a, b, c, d, e, and f) that during El Nino events the stream flows in Peru are found to be above the normal whereas the stream flows in the Murray River, Australia show a decreasing trend during these events. But these plots fail to spot any pattern for River Jamari in Brazil, Chennai precipitation and streamflows in Rappahannock River in USA. This can be attributed to various factors which influence the studies in a great way. Firat of all the dataset chosen only has a limited number of El Nino and La Nina events (23 El Nino and 14 La Nina) which might not a good representation of the phenomena as a whole. Our confidence in the result would have increased if there were more El Nino and La Nina events to draw any conclusion from the study.

The fact that there exist so numerous techniques to identify the El Nino/ La Nina years (Section 6.3) might also be a question for concern. It has been also noticed that all these techniques give different results making it very difficult to perform the analyses and identify the changes. Since the El Nino/ La Nina years used in the analysis are based on SOI, which uses just the sea level pressures at two points, the dependence on the global climate on might be a big question which remains to be answered. Probably, SST based classification of El Nino/ La Nina years might be more correct to represent the changes in the particular region and hence on global climate.

One important factor in not observing any specific trend for the streamflows in Rappahannock River may be the size and location of the watershed. The watershed is much small compared to the other watersheds studied in the report which makes more difficult to identify the extent of the changes in the streamflow in the watershed. A bigger watershed in the different part of the Virginia state might give a better representation of the effects of El Nino / La Nina events on the climate of the Virginia.

9. Summary of the work done

9.1 Summary

This work was aimed at the calculation of safe yield of the jointly operated system of reservoir using a binary integer linear programming optimization model and estimating the effects of the ENSO events on the safe yield for reservoir system.

A binary integer linear programming optimization model was developed for most general jointly operated system of reservoir where the reservoirs work in conjunction to fulfil the water demands of any locality. Application of this model was demonstrated on a jointly operated reservoir system in Spotsylvania in northern Virginia, USA, where three reservoirs work in conjunction. Among the constraints in the model were the instream requirement to maintain the fish habitat and recreational purposes, capacity of the pumping station at the reservoir sites, water treatment plant capacities at the respective reservoirs and the storage capacities of the reservoirs. Safe yield for the reservoir system is thus calculated and it was found that the system could be able to support more releases than individual operation of the reservoirs. The instream requirements and the water treatment plant capacities were found to be the factors which limit the safe yield for the whole system. Increased water treatment plant capacities for the water treatment plants were proposed from this work.

Furthermore, to evaluate the change in the safe yield due to the climatic phenomena, ENSO were studied and their effects on the stream flows and precipitation in the study region were analyzed. To quantify the ENSO phenomena, different methods to calculate the pressure and temperature indices were studied. Classifications of ENSO years were studied and it was found that these methods fail to agree among themselves with the identification of ENSO events. To establish a change in streamflow and precipitation pattern in the study region as well as four other regions across the world are studied with respect to pressure index (SOI). Various methods such as lag correlation analysis and descriptive analysis were used to find a change in the stream flows/ precipitation across these regions. Using these studies, only the Australian river and Peru river are found to be experiencing the significant change with the El Nino and La Nina events. The streamflow for Rappahannock river in northern Virginia, USA failed to show any change in the streamflow during these events which led us to conclude that this region is unaffected by ENSO events. There might be several factors for not getting any change, one of them might be the geographical location and the size of the watershed. Rappahannock river at north Virginia has a very small drainage area as comapared to other rivers considered in the study due to which the river might fail to show any significant change in the streamflows. Further work is needed to consider a river with bigger watershed in the region, which might show some changes on the stream flows due to these events.

9.2 Scope of Further Work

This work opens the doors for further research in other areas, which need to be further studied and looked into. In the calculation of safe yield, this work does not consider the demands of the region due to non-availability and ever changing nature of the data. An effort can be made to come up with a methodology to estimate the water demands of the locality and this can be included in the safe yield model to better predict the safe yield based on the demands of the region. In this work, season varying releases are not considered which might be a big factor since in real life operating policy of the reservoirs change because of the seasonal effects due to change in the inflows, temperature, demands.

During the studies on ENSO events, various indices to quantify the events are studied. Various methods were found to calculate same index (SOI), for example NOAA and Troupe SOI. An effort can be made to establish a relation between these indices. A lot of different methods which are being used by different agencies are studied and it is shown that they do not agree among themselves on the identification of the ENSO events. An effort should be made to come up with a methodology to identify these events based on the indices. While studying the effects of ENSO events on the stream flows / precipitation in five different regions of the world, Rappahannock river in north Virginia along with Brazilian river and Chennai, India precipitation fail to show any change in pattern. This might have been because of the identification of the ENSO years. Different method to identify these years might facilitate identification of a pattern in these region.

Inclusion of a river in north Virginia with larger drainage area in the studies might also be an area of further studies to identify the change in streamflow pattern in this part of the country.

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