NIWA
Taihoro Nukurangi

Kiribati Adaptation Programme. Phase II: Information for Climate Risk Management

High intensity rainfall and drought

NIWA Client Report: WLG2008-12
July 2008
Updated April 2010

NIWA Project: GOK08201

Kiribati Adaptation Programme. Phase II: Information for Climate Risk Management

High intensity rainfall and drought

Craig Thompson
Brett Mullan
Stuart Burgess

NIWA contact/Corresponding author

Doug Ramsay

Prepared for

Government of Kiribati

NIWA Client Report: WLG2008-12
July 2008
Updated April 2010

NIWA Project: GOK08201

National Institute of Water & Atmospheric Research Ltd
301 Evans Bay Parade, Greta Point, Wellington
Private Bag 14901, Kilbirnie, Wellington, New Zealand
Phone +64-4-386 0300, Fax +64-4-386 0574
www.niwa.co.nz

Contents

Reviewed by:

Andrew Tait

Approved for release by:

Doug Ramsay

Formatting checked:

Executive Summary

Headline statements from the Intergovernmental Panel for Climate Change (IPCC) Fourth Assessment Report released in 2007 concluded that:

- "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level."

- "Most of the observed increase in globally averaged temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations."

Based on 12 Global Climate Models for the Kiribati region, by the 2090s (2090-2099), average temperatures are likely to rise (relative to the average temperatures between 1980-1999) by:

- +1.2 ºC for a low emission scenario.

- +2.6 ºC for a medium emission scenario.

- +5.6 ºC for a high emission scenario.

All Global Climate Models suggest that average rainfall amounts will increase in Kiribati under a warmer climate.

Under a warmer climate the intensity of extreme rainfall events will also increase. The magnitude of change in rainfall intensity will depend on how much temperature rise occurs and on the particular severity and duration of the extreme rainfall.

An analysis of drought duration for Kiribati rainfall sites indicates that for the majority of locations 70 to 80 percent of droughts last up to 10 months, although there is a sizeable fraction of droughts that persist for over a year. A frequency analysis of drought duration suggests droughts of 12 months duration are expected on average once every 5 to 10 years. Further, very persistent droughts (i.e., lasting for at least 2 years) do occur relatively infrequently and especially during La Niñas, and can be expected on average once every 20 to 50 years.

The joint recurrence interval of drought intensity and duration was also evaluated for Kiribati. The most severe droughts have the largest recurrence intervals (i.e., are the rarest), and occur during long periods of extremely low rainfall. While this is a fairly obvious, the methodology presented in this report allows properties of these rare events to be quantified. This should be useful to government

agencies in assisting them to determine water requirement and water conservation strategies during times of adverse climate conditions, such as extended La Niña periods.

At present the climate models do not provide a consistent picture on future changes in intensity and frequency for El Niño and La Niña events. Hence, there is less understanding of how drought may change in the future, but it is likely that for Tarawa:

- Drought characteristics will generally stay much the same over the next 100 years.
- There will be some periods when drought may be slightly more prevalent during this time.

The information contained within this report allows probabilistic assessment (annual exceedence probabilities from 50% to 1%) of:

- 10 minute to 72 hour rainfall intensities for Tarawa and Banaba for the present day, 2025, 2050 and 2100.
- 1 to 3 day rainfall intensities for 6 other Kiribati islands for the present day, 2025, 2050 and 2100.
- Drought durations for 23 locations for the present day and an assessment of how drought duration may change for Tarawa over the next 100 years.
- Joint occurrences of drought severity and duration for 22 locations.

Following this report being finalised a further three future climate change scenarios and three particular timeframes were selected by the I-Kiribati participants in the training workshops to be used for routine climate change assessments that were appropriate for Kiribati. This report has been updated to include these additional temperature change scenarios.

1. Introduction

1.1 Project overview

The Government of Kiribati (GoK) commissioned NIWA to carry out one of the components (KAP II Component 1.4.0 FS5) of Phase II of the Kiribati Adaptation Project. The overall objective of Phase II is to *implement pilot adaptation measures, and consolidate the mainstreaming of adaptation into national economic planning*.

The objective of this particular component is to develop climate risk information to be adopted as national standards for options analysis and technical design work ("climate proofing parameters"), particularly regarding coastal and water related issues.

This report focuses on the rainfall and drought related aspects of the project. Coastal aspects are covered in a subsequent report (Ramsay et al. 2008).

1.2 Scope of the rainfall and drought component of the project

The terms of reference (contained in full in Appendix 1) for the project specified the following to be conducted for the high intensity rainfall and drought aspects of the project:

- Analysis on intensity of extreme rainfall events with an average recurrence interval of 10, 50 and 100 years, as well as droughts with an average recurrence interval of 10, 50 and 100 years.

- Identify combined scenarios of the risk of extreme rainfall and drought for three time horizons, 2025, 2050 and 2100.

In conjunction with the coastal aspects in house training on the use and application of the data derived as part of this project will be conducted along with assistance in integrating climate risk information into awareness products.

1.3 Outline of this report

The outline of this report is as follows. In Section 2 details of the rainfall archive and data used in the various analyses are provided for all available sites in the NIWA climate archive. An analysis of high intensity extreme rainfalls is given in Section 3

where depth-duration-frequency tables are given for a range of rainfall recurrence intervals and for a range of durations.

In Section 4 a detailed drought analysis, based on a rainfall deficit index method is provided for Kiribati. Section 5 provide information on the climate change scenarios adopted for the 21st century from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change for Kiribati, and how climate change may impact high intensity rainfall and drought.

Appendices provide the full terms of reference, a glossary of terms used in this report, more information on some of the analysis methodologies and further tables and figures of rainfall depth and drought results.

Reference should also be made to the training material (contained on the supporting CD to this report) that was presented during the workshops carried out in Tarawa during March 2008.

Following this report being finalised a further three future climate change scenarios and three particular timeframes were selected by the I-Kiribati participants in the training workshops to be used for routine climate change assessments that were appropriate for Kiribati. This report has been updated to include these additional temperature change scenarios. These are contained in appendix 9.

1.3.1 Using the information in this report

There are a number of "How to" sections throughout the report that explain and demonstrate using worked examples how to use and apply the information contained within this report.

A simple spreadsheet tool (Rainfall calculator version 4.3) was also developed and used in the training workshops. The spreadsheet acts as a database for the information contained in the report and can be used to:

- Create tables of present-day depth-duration-frequency rainfall values for the Kiribati islands where sufficient data was available.

- Create tables of future depth-duration-frequency rainfall values for the 2025s, 2050s and 2090s for low, medium and high emission scenarios.

- Create plots of rainfall depths for a range of recurrence intervals (ARI) comparing the present day and a future timeframe/emission scenario.

- Create tables and plots of different average recurrence intervals for drought duration for any of the Kiribati Islands.

- Calculate the drought severity index (DSI) for a period of low rainfall for any of the Kiribati islands.

The spreadsheet is contained on the accompanying CD along with instructions on how to use it.

For users of the information contained in this report, the following provides a quick summary of the relevant information sources and their location within the report:

	Data Location	Example of how to use the data	Available in rainfall calculator
High intensity rainfall information:			
• **Present day:** Depth-duration-frequency tables	Tables 2 & 3	Sec. 3.1	✓
• **Future:** Depth-duration-frequency tables (2025, 2050 & 2100)	Appendix 8	Sec.5.3	✓
Drought:			
• **Present day:** Drought duration average recurrence intervals	Table 4	Sec 4.7.1	✓
• **Present day:** Drought duration cumulative probabilities	Appendix 6	Sec. 4.7.2	
• **Present day:** Joint probabilities of drought duration and intensity	Appendix 7	Sec 4.7.3	✓
• Calculating Drought Severity Index, DSI	Appendix 4		✓
• **Future:** Drought duration average recurrence intervals for 2025, 2050 and 2100 for Tarawa	Table 10		

2. Rainfall archive and data

2.1 Available rainfall data

The climate database (CLIDB) maintained by NIWA is a New Zealand nationally significant archive. CLIDB contains a large variety of climate and weather records from New Zealand, the Pacific Islands and Antarctica. Earliest climate records are from the mid nineteenth century. The database comprises of mostly electronic records together with a comparatively small holding of paper records that are still to be stored on CLIDB.

The archive of Pacific Island climate and weather data contains paper and electronic records from 716 sites spread across the North and South Pacific Ocean. Island nations with significant data holding in CLIDB include Cook Island, Fiji, French Polynesia, Kiribati, New Caledonia, Nuie, Samoa, Tokelau Islands, Tuvalu and Vanuatu. The majority of sites record just rainfall.

A listing of sites in Kiribati where climate data is held on CLIDB is provided in Table 1 together with the length of record contained in the database. At most sites in the table, there are periods of missing data and not all the available climate data for Kiribati is currently archived in CLIDB. NIWA has a scientific programme of data entry for paper climate records from Pacific Island nations into CLIDB, which is ongoing and is expected to be completed at the end of 2008. From the listing of sites in Table 1, analyses of extreme rainfall and of drought were performed at the sites with a sufficient length of dataset to permit such analysis. Results of these analyses appear in later sections of the report.

Table 1: Details of climate and rainfall sites in Kiribati with records held in CLIDB.

Site No.	Site Name	Latitude (°)	Longitude (°)	Period of Record
J48300	Washington Is (Teraina)	4.717 N	160.433 W	1947-1990
J48700	Fanning Is (Tabuaeran)	3.850 N	159.367 W	1931-2002
J48900/J49000	Christmas Is (Kiritimati)	1.983 N	157.483 W	1949-2006
J49001	Banana (on Kiritimati)	1.983 N	157.350 W	1984-1991
J49002	Manulu (on Kiritimati)	1.950 N	157.383 W	1984-1994
J53300	Banaba	0.900 S	169.550 E	1904-1998
J60100	Butaritari	3.067 N	172.783 E	1945-2006
J60101	Makin	3.283 N	172.967 E	1955-1990
J60400	Marakei	2.050 N	173.250 E	1954-1995
J60700	Abaiang	1.817 N	173.017 E	1950-1992
J61000	Tarawa	1.350 N	172.933 E	1947-2007
J61001	Abaokoro (on Tarawa)	1.483 N	173.000 E	1977-1990
J61002	Bonriki (on Tarawa)	1.383 N	173.133 E	1982-1992
J61003	Bikininbeu (on Tarawa)	1.350 N	173.083 E	1987-1987
J61200	Bonriki Int (on Tarawa)	1.383 N	173.150 E	1997-1997
J61300	Maiana	0.917 N	173.067 E	1955-1988
J61500	Abemama	0.400 N	173.917 E	1944-1992
J61501	Abemama [2]	0.383 N	173.917 E	1985-1997
J61600	Kuria	0.200 N	173.383 E	1955-1994
J61700	Aranuku	0.167 N	173.600 E	1955-1995
J62000	Nonouti	0.667 S	174.333 E	1953-1991
J62100	Tabiteuea N	1.200 S	174.733 E	1958-1991
J62200	Tabiteuea S	1.500 S	175.067 E	1960-1991
J62300	Beru	1.350 S	175.983 E	1944-2002
J62400	Nikunau	1.333 S	176.433 E	1955-1992
J62500	Onotoa	1.817 S	175.550 E	1953-1996
J62600	Tamana	2.500 S	175.967 E	1950-1996
J62900	Arorae	2.633 S	176.800 E	1950-2002
J70000	Canton Is (Abariringa)	2.817 S	171.717 W	1937-1967
J70100	Kanton Is (Abariringa)	2.767 S	171.717 W	1983-2006
J70500	Gardiner Is (Nikumaroro)	4.667 S	174.550 W	1951-1963
J71000	Hull Is (Orona)	4.500S	171.233 W	1953-1963
J71100	Sydney Is (Manra)	4.450 S	171.263 W	1948-1961

2.2 Rainfall monitoring issues and needs

Over much of the 20th century, Kiribati had a very comprehensive rainfall monitoring network. However, over the last 10 to 20 years this network has deteriorated significantly to the point that the only rainfall records now being collected consistently is at Tarawa. Monthly rain data is also collected at Butaritari, Canton and Christmas Islands. This has significant implications for assessing extreme rainfall and drought conditions on Kiribati, to better assess and monitoring how these conditions may change under both natural climate variability and climate change, and to reduce the uncertainties associated with such assessments.

Unless there is a major reversal in the extent of the rainfall monitoring network throughout Kiribati, this deterioration will have a significant impact on the ability to make future informed decisions on adaptation needs. It is understood that a review of meteorological monitoring, and upgrading of the network, is under discussion in another component of the KAP II project.

3. High intensity rainfall in Kiribati

Annual maximum rainfalls for durations from 10 minutes to 72 hours and for 1 to 3-days durations were extracted from NIWA's climate database, CLIDB. For 10 minute to 72 hour rainfall durations, the annual maxima had been extracted from automatic pluviographs (available for Tarawa and Banaba only), while for the 1 to 3-day rainfall durations, data have been obtained from manual rain gauges read once daily in the morning (Fanning Island (Tabuaeran), Christmas Island (Kiritimati), Banaba, Butaritari, Tarawa, Beru, Arorae and Kanton (Abariringa)). Annual maximum series at each site were used if each annual value came from a year with at least 11 months of records, and if there were at least 10 years of records in each series. Annual maximum series are used when assessing the frequency of high intensity and rare-event extreme rainfalls. Appendix 3 provides details of the extreme value analysis theory commonly used to estimate the recurrence intervals or exceedance probabilities of the high intensity rainfall.

Tables 2 and 3 give depth-duration-frequency tables for the Kiribati rainfall recording sites with sufficient availability of data for an extreme analysis. Table 2 provides extreme rainfall estimates for durations from 10 minutes to 72 hours at Tarawa and Banaba. Table 3 provides estimates of 1 to 3 day duration rainfall intensities derived from manual rain gauge data. The 1 – 3 day rainfalls have not been adjusted to account for their fixed observational time to provide estimates of their equivalent 24 – 72 hour rainfall. Such fixed time data rarely provides the true maximum amounts for the indicated durations, and as such will produce lower rainfall depths when compared to a corresponding analysis using data that is not constrained by the observation time. This can be seen in the depth-duration-frequency tables for Tarawa and Banaba. The differences are larger at 1-day/24-hours and are in the order of 17 percent, while the difference at 3-days/72-hours is in the order of 7 – 10 percent.

The parameters of the extreme value distribution (i.e., a Gumbel distribution) are also given for each site in Appendix 3 (Table 3.1). These parameters can be used to provide rainfall estimates at other average recurrence (ARI) intervals not given by the tables using the appropriate formula in Appendix 3.

The average recurrence interval of a storm's rainfall, also known as return period, is a measure of its rarity, and is defined as the average time interval between rainfalls of a specified magnitude. The longer the recurrence interval, the rarer the storm event. The average recurrence interval, T_A, can lead to confusion and it is frequently expressed in probabilistic terms as the annual exceedance probability, (AEP). For annual maximum rainfalls used in this report:

$AEP = Prob(Annual\ Maximum > X) = 1/T_A$.

A comparison between the AEP and recurrence interval, T_A, is provided in Table 3.2 in Appendix 3.

For example, a rainfall intensity with an ARI (or return period) of 50 years, has an annual exceedance probability of 0.02 (or 2%), that is a 2% chance of the rainfall intensity being equalled or exceeded in any one year.

Table 2: Depth (mm) – duration (minutes & hours) – frequency (years) for Banaba (top) and Tarawa (bottom).

Banaba (1972-1988)		**Duration**									
ARI (years)	**AEP (%)**	**10 min**	**20 min**	**30 min**	**1 hr**	**2 hr**	**6 hr**	**12 hr**	**24 hr**	**48 hr**	**72 hr**
2	**50%**	19.0	30.2	36.4	60.1	74.1	98.1	120.3	133.2	156.6	178.7
5	**20%**	22.3	35.7	44.8	77.8	106.4	143.3	175.8	190.6	216.5	245.7
10	**10%**	24.4	39.4	50.4	89.6	127.7	173.3	212.6	228.6	256.1	290.1
20	**5%**	26.4	43.0	55.7	100.8	148.3	202.1	247.9	265.0	294.1	332.6
50	**2%**	29.1	47.6	62.6	115.4	174.8	239.3	293.6	312.2	343.3	387.7
75	**1.3%**	30.3	49.6	65.6	121.8	186.5	255.6	313.6	332.9	364.9	411.9
100	1%	31.1	51.0	67.8	126.3	194.7	267.2	327.8	347.5	380.1	429.0

Tarawa (1971-1994)		**Duration**									
ARI (years)	**AEP (%)**	**10 min**	**20 min**	**30 min**	**1 hr**	**2 hr**	**6 hr**	**12 hr**	**24 hr**	**48 hr**	**72 hr**
2	**50%**	19.1	29.3	36.8	49.6	63.7	100.1	115.9	128.3	149.6	163.4
5	**20%**	24.8	38.5	46.5	63.3	81.7	133.5	157.1	175.4	203.1	220.7
10	**10%**	28.5	44.6	52.9	72.4	93.7	155.6	184.4	206.6	238.5	258.7
20	**5%**	32.1	50.4	59.0	81.1	105.1	176.8	210.6	236.5	272.5	295.1
50	**2%**	36.7	58.0	67.0	92.4	120.0	204.3	244.4	275.3	316.4	342.2
75	**1.3%**	38.7	61.3	70.4	97.3	126.5	216.3	259.3	292.3	335.7	362.8
100	**1%**	40.1	63.6	72.9	100.8	131.1	224.9	269.8	304.3	349.4	377.5

Table 3: Depth (mm) – Duration (days) – Frequency (years) for sites in Kiribati.

Fanning Island (Tabuaeran) (1971-1999)					Christmas Island (Kiritimati) (1953-2000)				
ARI (years)	**AEP (%)**	**1-day**	**2-day**	**3-day**	**ARI (years)**	**AEP (%)**	**1-day**	**2-day**	**3-day**
2	**50%**	109.7	140.8	160.1	**2**	**50%**	77.1	94.4	108.0
5	**20%**	147.1	183.9	211.2	**5**	**20%**	130.5	158.1	184.4
10	**10%**	171.9	212.4	245.1	**10**	**10%**	165.8	200.3	234.9
20	**5%**	195.7	239.8	277.5	**20**	**5%**	199.7	240.7	283.4
50	**2%**	226.4	275.2	319.5	**50**	**2%**	243.6	293.1	346.1
75	**1.3%**	239.9	290.8	338.0	**75**	**1.5%**	262.9	316.1	373.6
100	**1%**	249.5	301.8	351.0	**100**	**1%**	276.5	332.4	393.1

Banaba (1971-1997)					Butaritari (1971-1999)				
ARI (years)	**AEP (%)**	**1-day**	**2-day**	**3-day**	**ARI (years)**	**AEP (%)**	**1-day**	**2-day**	**3-day**
2	**50%**	114.0	144.7	162.8	**2**	**50%**	132.9	163.2	186.2
5	**20%**	158.3	195.6	222.1	**5**	**20%**	183.8	227.8	258.8
10	**10%**	187.7	229.4	261.3	**10**	**10%**	217.5	270.5	306.9
20	**5%**	215.8	261.7	299.0	**20**	**5%**	249.8	311.6	353.0
50	**2%**	252.2	303.6	347.7	**50**	**2%**	291.7	364.7	412.7
75	**1.3%**	268.2	322.0	369.1	**75**	**1.5%**	310.0	388.0	438.8
100	**1%**	279.5	335.0	384.2	**100**	**1%**	323.0	404.5	457.4

Tarawa (1948-2000)					Beru (1945-1991)				
ARI (years)	AEP (%)	1-day	2-day	3-day	ARI (years)	AEP (%)	1-day	2-day	3-day
2	**50%**	109.3	137.4	153.0	**2**	**50%**	91.8	111.9	128.2
5	**20%**	152.0	190.3	210.6	**5**	**20%**	135.0	161.2	188.7
10	**10%**	180.3	225.4	248.8	**10**	**10%**	163.6	193.9	228.7
20	**5%**	207.5	259.1	285.5	**20**	**5%**	191.1	225.3	267.1
50	**2%**	242.6	302.6	332.9	**50**	**2%**	226.6	265.9	316.8
75	**1.3%**	258.0	321.8	353.7	**75**	**1.5%**	242.1	283.7	338.6
100	**1%**	268.9	335.3	368.5	**100**	**1%**	253.2	296.3	354.0

Arorae (1971-1997)					Kanton Island (Abariringa) (1948-2000)				
ARI (years)	AEP (%)	1-day	2-day	3-day	ARI (years)	AEP (%)	1-day	2-day	3-day
2	**50%**	109.0	134.1	153.0	**2**	**50%**	81.8	101.3	115.9
5	**20%**	144.0	178.6	205.7	**5**	**20%**	126.9	156.8	181.6
10	**10%**	167.2	208.0	240.7	**10**	**10%**	156.7	193.6	225.0
20	**5%**	189.4	236.3	274.2	**20**	**5%**	185.3	228.9	266.7
50	**2%**	218.2	272.8	317.6	**50**	**2%**	222.4	274.5	320.7
75	**1.3%**	230.8	288.9	336.6	**75**	**1.5%**	238.7	294.6	344.3
100	**1%**	239.7	300.2	350.1	**100**	**1%**	250.2	308.8	361.1

3.1 How to use the High Intensity Rainfall Results

3.1.1 Rainfall depth worked example

To obtain an extreme rainfall depth for a rainfall site in Kiribati:

1. Go to the relevant table (Table 2 or 3) for the location of interest.

2. For the required storm duration and average recurrence interval (ARI) or AEP of interest at that site, find the appropriate rainfall depth in millimetres from the table.

We want to know what the present day rainfall depth is for a 2 hour duration rainfall with an Annual Exceedance Probability (AEP) of 5% (that is the amount of rain we would expect to fall in any 2 hour period on average every 20 years).

From Table 2 for Banaba:

- Find the column corresponding to the 2 hour rainfall duration.
- Find the row corresponding to the 5% Annual Exceedance Probability (AEP).

Banaba (1972-1988)		Duration									
ARI (years)	AEP (%)	10 min	20 min	30 min	1 hr	2 hr	6 hr	12 hr	24 hr	48 hr	72 hr
2	50%	19.0	30.2	36.4	60.1	74.1	98.1	120.3	133.2	156.6	178.7
5	20%	22.3	35.7	44.8	77.8	106.4	143.3	175.8	190.6	216.5	245.7
10	10%	24.4	39.4	50.4	89.6	127.7	173.3	212.6	228.6	256.1	290.1
20	5%	26.4	43.0	55.7	100.8	148.3	202.1	247.9	265.0	294.1	332.6
50	2%	29.1	47.6	62.6	115.4	174.8	239.3	293.6	312.2	343.3	387.7
75	1.3%	30.3	49.6	65.6	121.8	186.5	255.6	313.6	332.9	364.9	411.9
100	1%	31.1	51.0	67.8	126.3	194.7	267.2	327.8	347.5	380.1	429.0

1. The corresponding rainfall depth (in mm) is obtained from where the row and column intersect.
2. The rainfall depth for a 5% AEP, 2 hour rainfall duration, is 148.3 mm.

In a similar way daily rainfall extreme value depths can be obtained for a number of Kiribati Islands from Table 3. For example, we want to know what the present day 1% AEP rainfall depth is for a 3 day duration rainfall event in Butaritari.

From Table 3:

- Find the column corresponding to the 3 day rainfall duration.
- Find the row corresponding to the 1% Annual Exceedance Probability (AEP).

Banaba (1971-1997)					Butaritari (1971-1999)				
ARI (years)	AEP (%)	1-day	2-day	3-day	ARI (years)	AEP (%)	1-day	2-day	3-day
2	50%	114.0	144.7	162.8	2	50%	132.9	163.2	186.2
5	20%	158.3	195.6	222.1	5	20%	183.8	227.8	258.8
10	10%	187.7	229.4	261.3	10	10%	217.5	270.5	306.9
20	5%	215.8	261.7	299.0	20	5%	249.8	311.6	353.0
50	2%	252.2	303.6	347.7	50	2%	291.7	364.7	412.7
75	1.3%	268.2	322.0	369.1	75	1.5%	310.0	388.0	438.8
100	1%	279.5	335.0	384.2	100	1%	323.0	404.5	457.4

- The corresponding rainfall depth (in mm) is obtained from where the row and column intersect.

- The rainfall depth for a 1% AEP, 3 day rainfall duration at Butaritari, is 457.4 mm. In other words this rainfall depth would be expected to occur over 3 days on average every 100 years.

3.1.2 Rainfall intensity

For rainfall intensity instead of rainfall depth, this can be computed from the depth – duration –frequency tables (Tables 2 and 3) by dividing the rainfall depth by the given storm duration. Note the first three duration columns in Table 2 are storm durations in minutes and need to be converted into their corresponding durations in hours by dividing the minutes by 60. For example: a 10 minute duration is 0.167 hours and the values for 20 and 30 minutes are 0.33 and 0.5 hours respectively.

Using the Banaba example from above, the rainfall depth for a 5% AEP, 2 hour rainfall duration, is 148.3 mm. The rainfall intensity for this event is:

- 74.2 mm/hour (i.e., 148.3 mm / 2 hours).

For the Butaritari example, the rainfall depth for a 1% AEP, 3 day (i.e., 72 hour) rainfall duration, is 457.4 mm. The rainfall intensity for this event is:

- 6.4 mm/hour (i.e., 457.4 mm / 72 hours).

4. Drought

4.1 Introduction

The absence of rivers and lakes in Kiribati means that regular and reliable rainfalls are essential to maintain supplies of fresh water for the health and well-being of its citizens. On the small islands of Kiribati, water is sourced primarily from rain water stored in tanks, and from water well extraction from the small underground fresh water aquifers beneath coral atolls. During periods of low rainfall, ground water supplies can be reduced, and there may be a significant risk of salt water intrusion into the fresh water lens. The rainfall climate of Kiribati is extremely variable from year-to-year, with mean annual rainfalls from less than 1000mm in Eastern Kiribati, to over 3000mm in Western Kiribati (Porteous and Thompson, 1996). Rainfall is also influenced by the El Niño-Southern Oscillation phenomenon (White et al. 1999): rainfall tends to be higher during El Niño years and lower during La Niña years. One consequence of inherently variable rainfall is a climate that is prone to "drought", or periods of below average rainfall[1].

4.2 A measure of drought severity

Drought is often characterized by occurrence, duration and a measure of severity, and indices of drought are derived principally from rainfall records. In this report, a drought severity index, DSI, as proposed by Phillips and McGregor (1998) is used to assess the frequency of duration and intensity of droughts in Kiribati. DSI is calculated from monthly rainfalls and is derived using a rainfall deficit-index method that uses rainfall anomalies to monitor monthly rainfall surpluses and deficits or droughts. Other indices can be used, and White et al. (1999) analysed a number of indices, including a rainfall deficit index, in their study of drought in Tarawa.

Details of the method of computing the drought severity index are provided in Appendix 4 and definitions to characterize drought are given as follows. A *drought event* is a set of DSI values that exceeds onset and termination criteria for drought, and *drought duration* is the length of the drought event. The area under the individual DSI values (see for example Figure 1) measures the *drought magnitude*, and the *drought*

[1] This suggests a meteorological definition for drought, although other possibilities such as hydrological drought, agricultural drought etc. could also have been used.

intensity is the ratio of the drought magnitude to the duration of the drought event. Both magnitude and intensity are measures of drought severity.

Two examples of time series of the DSI are given for Banaba (Figure 1) and Tarawa (Figure 2). The figure for Banaba shows an extensive index of drought almost spanning the 20th century, although there is a substantial gap in the rainfall record during the 1940s and 1950s. Drought conditions, of variable severity, occur on average in 6 years every decade, and on occasion will persist for more than 18 months. At Tarawa, which covers just the second half of the 20th century, it is immediately noticeable that although droughts occur just as often as it does at Banaba (i.e., about 7 events every decade) and can also persist for more than 18 months, the severity of each event is much smaller (note the different scale on the y-axis). This can also be seen in histograms of drought duration for Banaba and Tarawa in a series of diagrams presented in Appendix 6.

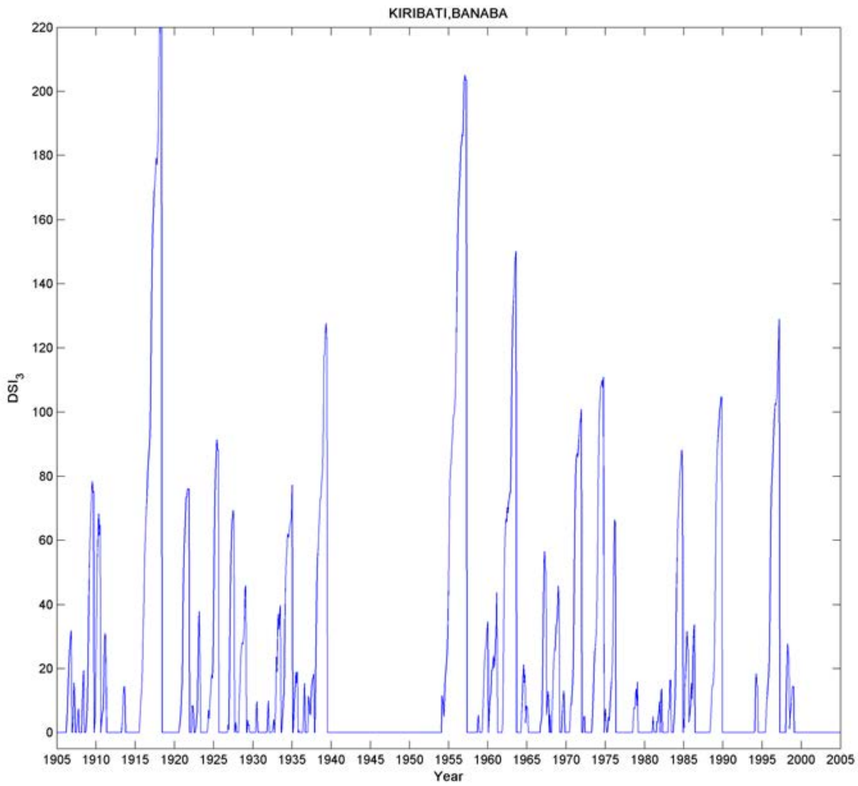


Figure 1: The occurrence of drought at Banaba, Kiribati derived from the Phillips and McGregor drought severity index (DSI). Note the gap in the drought index during the 1940s and first half of the 1950s due to missing data.

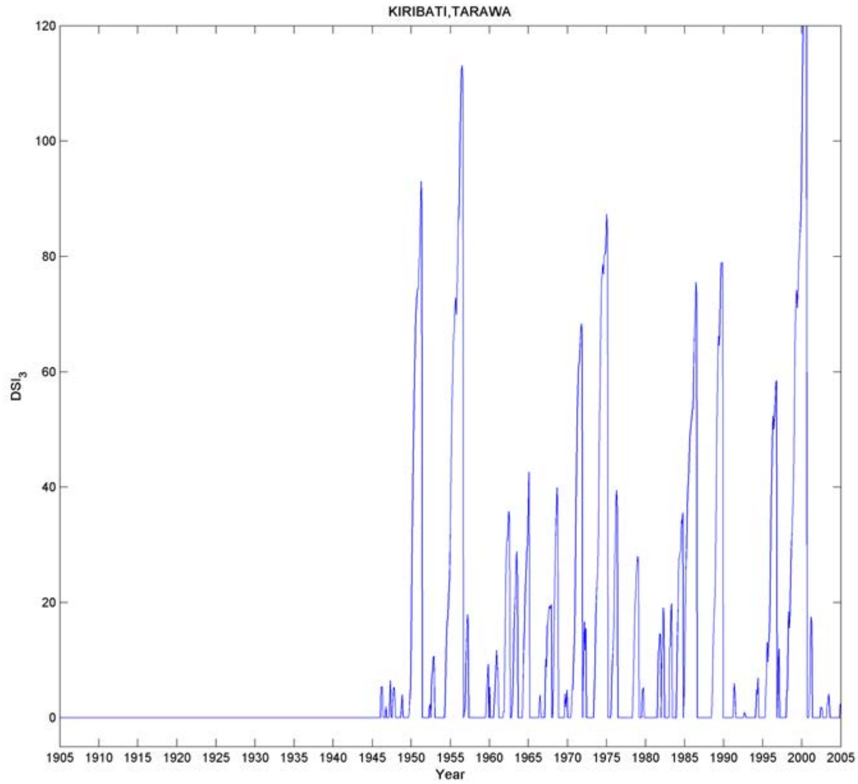


Figure 2: The occurrence of drought at Tarawa, Kiribati derived from the Phillips and McGregor drought severity index (DSI). Note the gap in the drought index during the first half of the 20th century.

4.3 Frequency analysis of drought

As drought is often characterized by occurrence and severity, a general approach in any drought analysis is to separately analyse such characteristics by performing frequency analyses on, say, drought duration and drought severity. However, drought is a multi-variable event (e.g., duration, magnitude, and intensity) which are not independent of one another and contain significant correlations among the drought properties. The frequency analysis undertaken in this report is described in Appendix 5. The analysis uses a distribution-free method, and (a) analyses the duration of droughts and (b) analyses jointly drought duration and drought intensity. The distribution-free method applies empirical probability density functions through the use of weighted moving-averages of the drought severity index in small regions around points of estimation.

4.4 Analysis of drought duration

Time series of drought duration were compiled from the drought severity index for the Kiribati rainfall sites, and histograms, empirical probability density and cumulative distributions were constructed. These are presented in Appendix 6. There are four panels to each figure. The upper left panel shows the time series of the Drought Severity Index, while the upper right panel shows histograms of drought duration. The lower left panel provides an empirical density function for drought duration, and is a smooth approximation of the histogram, while the lower hand panel provides the cumulative distribution of drought durations which can be used evaluate the recurrence intervals of drought in conjunction with the drought occurrence parameter, θ, in Table 4. The formulation of the recurrence interval for drought duration is also given in Appendix 5.

For the vast majority of rainfall sites, the figures in Appendix 6 indicate that between 70 and 80 percent of droughts persist for less than 10 months, but there are still a sizeable proportion of droughts that do persist for more than one year. At Kanton Island for example, which is displayed in Figure 3 and in Appendix 6, nearly 90 percent of droughts last up to 1 year. This has an expected recurrence interval (Table 4) of approximately 10 years. At all sites in Kiribati, Table 4 indicates droughts lasting for up to a year have recurrence intervals of between 5 and 10 years.

Table 4 also indicates that very persistent and long lasting droughts do occur in Kiribati. Such events do not occur frequently, and are especially likely during La Niña episodes. In Kiribati, droughts of at least 2 years duration can be expected about once every 20 to 50 years. How rare a drought event is very much dependent on the numbers of droughts that occur each year, and in Table 4 the drought occurrence rate parameter, θ, provides that indication: The smaller the θ, the longer the drought event for any given average recurrence interval.

Such an analysis as presented above provide no information on the severity or intensity of droughts, rather it indicates the likelihood of periods of consistently low rainfall in Kiribati. The multi-variable analysis of drought is presented in the next section when the joint distribution and average recurrence intervals of drought duration and intensity are analysed.

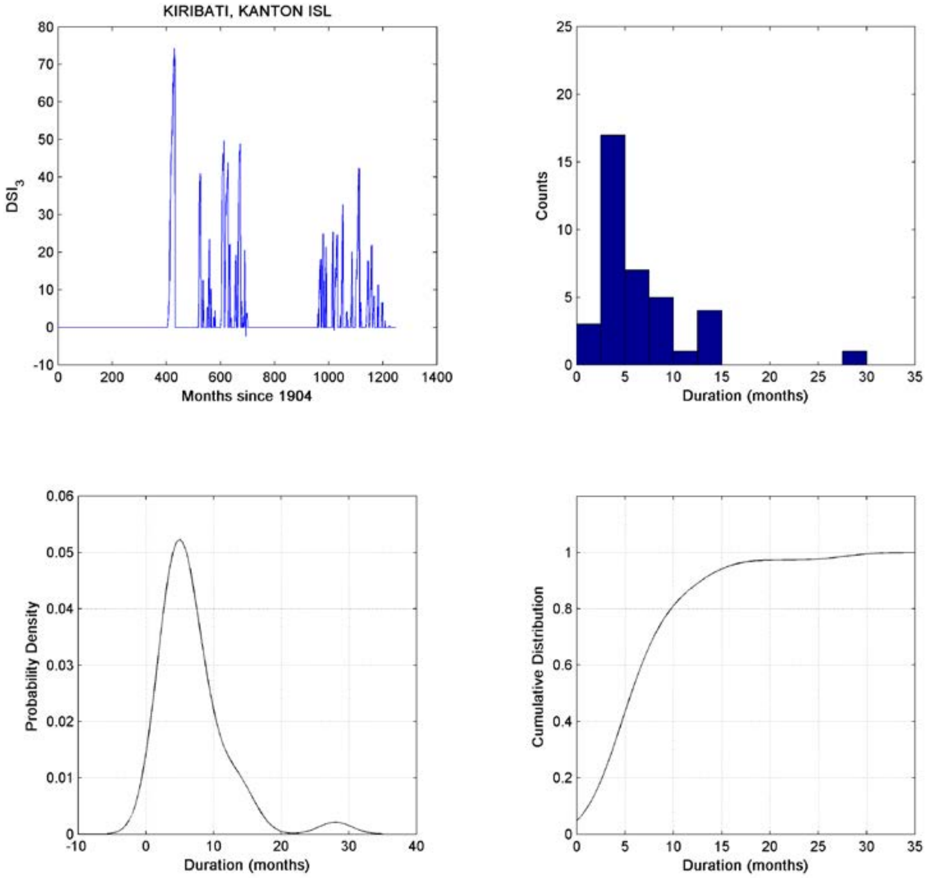


Figure 3: Diagrams of Drought Severity Index (DSI), Histogram of Drought Duration, Empirical Probability Density Distribution and Cumulative Distribution of Drought Duration at Kanton Island, Kiribati.

Table 4: Expected Drought Duration (months) for specified Average Recurrence Intervals (years) for rainfall sites in Kiribati. The variable θ gives the mean number of droughts per year in the observational record and is used in assessing the ARI of droughts. See Appendix 5 for details. Annual exceedance probabilities (% AEP) are provided in the row below the average recurrence intervals.

		ARI (years) / AEP (%)						
		2	5	10	20	50	75	100
Site	**θ**	**50%**	**20%**	**10%**	**5%**	**2%**	**1.3%**	**1%**
Washington Is	1.05	6	10	13	18	20	21	22
Fanning Is	0.91	5	11	15	19	24	27	29
Christmas Is	1.02	6	10	14	16	18	19	19
Banaba	0.63	3	13	18	22	32	36	37
Butaritari	0.90	5	11	15	20	27	31	33
Makin	0.94	5	12	16	20	23	24	25
Marakei	0.77	4	12	17	20	24	25	26
Abaiang	0.68	3	11	17	25	35	37	38
Tarawa	0.75	4	12	19	24	30	31	32
Maiana	0.68	5	12	16	24	32	34	35
Abemama	0.85	6	11	14	16	22	24	25
Kuria	0.86	5	11	16	21	24	25	26
Aranuka	0.81	4	11	16	23	30	31	32
Nonuti	0.81	5	11	15	18	27	29	30
Tabiteuea N	0.85	4	10	15	23	28	29	30
Tabiteuea S	0.83	5	11	16	20	24	25	25
Beru	0.68	4	12	18	23	27	29	30
Nikunau	1.00	6	11	14	16	18	19	19
Onotua	0.78	5	11	15	22	28	30	31
Tamna	0.74	5	13	17	22	29	30	31
Arorae	0.67	3	12	17	20	28	36	38
Canton	0.93	5	10	13	15	19	20	21
Kanton Is	1.00	6	10	13	16	26	28	28

4.5 Joint analysis of drought duration and drought intensity

In this section drought in Kiribati is treated as a two-variable event, where the joint average recurrence intervals of drought duration and drought intensity are analysed. Central to this analysis is the derivation of a joint probability distribution using a two-variable Gaussian kernel estimator (see Appendix 5 and Kim et al. 2003). An example of the joint probability density for duration and intensity is given in Figure 4 for Abemama. This three-dimensional graph shows a large peak in the joint probabilities,

and indicates the most common combination of drought duration and intensity from the Abemama drought severity index is for duration of 5 months and drought intensity of 5. There is also a minor joint probability peak for a duration of 50 months and an intensity of 25. This graph, which is typical of all the joint probability graphs for Kiribati, shows a principal axis in the diagonal direction due to the high correlation between duration and intensity.

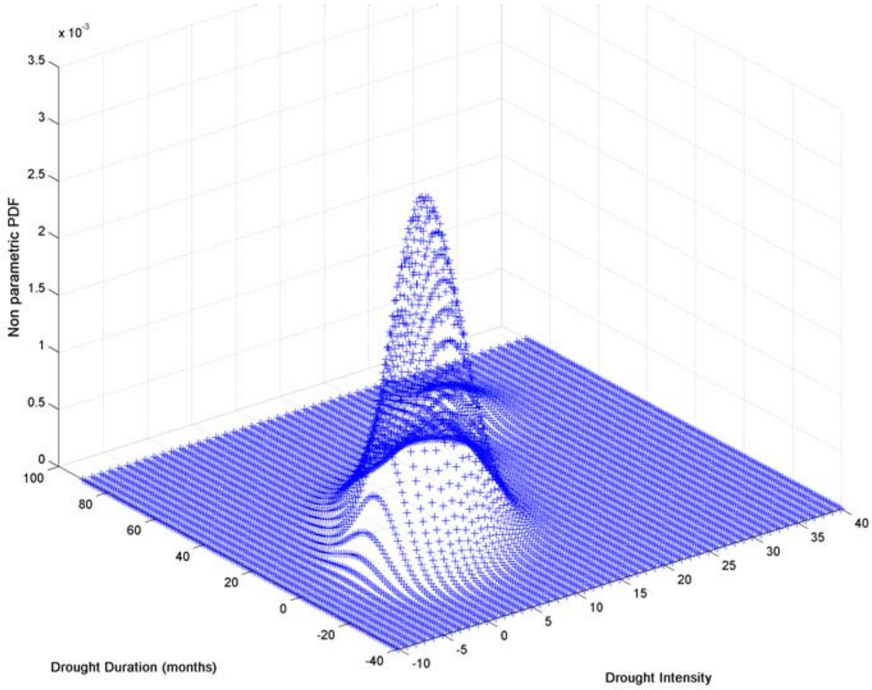


Figure 4: Joint probability density distribution for drought duration and intensity for Abemama.

The estimation of the joint average recurrence interval (or return period) of drought duration and intensity is given in Appendix 5, and is derived from a combination of the drought occurrence rate parameter, θ, and the joint cumulative distribution of duration and intensity. An example is given in Figure 5 for Abemama, and for all the Kiribati sites in Appendix 7. In these figures, the left panel provides the cumulative distribution of drought duration for a specified intensity. At Abemama, for example, a drought intensity value of 32 (i.e., i_o = 32) suggests about 85 percent of all droughts persist for less than 15 months, and those that do persist for longer have greater intensities. Nearly 100 percent of all droughts that persist for 3 years (i.e., 36 months) can be expected to have a drought intensity of less than 64.

The right panel in Figure 5 shows the relationship between drought duration and intensity in terms of the average recurrence interval. The diagram provides isolines of ARI for a range of durations and intensities. The diagram clearly shows the persistent long lasting droughts are more severe and intense than shorter duration droughts, and have the largest recurrence intervals. For example, a drought persisting for two years at Abemama with an intensity value of 20 can be expected to occur approximately once every 5 years (circled on the right-hand diagram), but if the drought is more severe, say 50, then this combination can be expected on average once every 40 years.

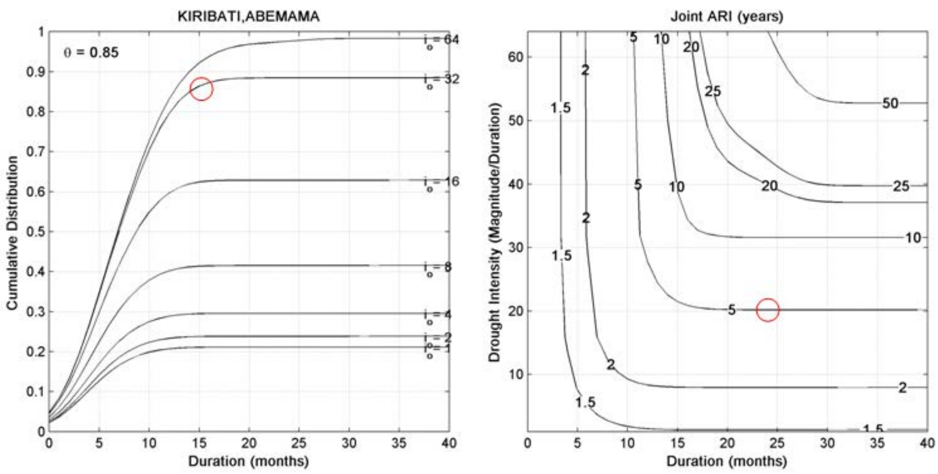


Figure 5: Joint Distribution of Drought Duration and Intensity for Abemama, Kiribati. The left panel shows the cumulative distribution of drought duration for specified drought intensities, i_o, and the hand panel shows the joint average recurrence interval in years. The circles in the diagrams are the points of intersection from the examples provided in the text.

4.6 Drought – concluding remarks

Drought in this report has been defined on the basis of a precipitation-deficit index method, and full details of determining the onset, continuation, and termination of a drought are given in Appendix 4.

Drought is a multi-variable event. Drought properties (i.e., duration, magnitude, and intensity) are not independent of one another and contain significant correlations, for example between duration and intensity. The joint average recurrence intervals of duration and intensity have been analysed simultaneously within the frequency analysis framework through the application of a two variable distribution-free joint probability density function. The analysis for Kiribati shows the joint recurrence interval increases with drought duration and intensity, and events with the largest average recurrence interval (i.e., rarest events) coincide with the very severe and long-

lasting droughts. As well as being a useful method in assessing the multivariate nature of droughts, these approaches can also be applied to assess water requirement and water conservation strategies by government agencies during times of persistent and severe droughts.

4.7 How to use the drought results

4.7.1 Drought duration (simple method) – worked example

To obtain the drought duration (in months) for a particular annual exceedance probability (AEP) for the present day (i.e., based on historical rainfall data):

1. From Table 4, select the required location in Kiribati.
2. Find the drought duration in months for the required Annual Exceedance Probability.

For Tarawa, what is the historical duration of a drought having an annual exceedance probability (AEP) of 5% (i.e., would be expected to occur once every 20 years on average):

- Find the row corresponding to Tarawa in Table 4.
- Find the column corresponding to the 5% Annual Exceedance Probability (AEP) in Table 4.

		ARI (years) / AEP (%)						
		2	5	10	20	50	75	100
Site	θ	50%	20%	10%	5%	2%	1.3%	1%
Washington Is	1.05	6	10	13	18	20	21	22
Fanning Is	0.91	5	11	15	19	24	27	29
Christmas Is	1.02	6	10	14	16	18	19	19
Banaba	0.63	3	13	18	22	32	36	37
Butaritari	0.90	5	11	15	20	27	31	33
Makin	0.94	5	12	16	20	23	24	25
Marakei	0.77	4	12	17	20	24	25	26
Abaiang	0.68	3	11	17	25	35	37	38
Tarawa	0.75	4	12	19	24	30	31	32
Maiana	0.68	5	12	16	24	32	34	35

- The corresponding drought duration is obtained from where the row and column intersect.

- For Tarawa the 5%AEP drought duration is 24 months. That is, we would expect a drought to last for 24 months about once every 20 years on Tarawa.

4.7.2 Drought duration (calculated) – worked example

Drought duration probabilities can also be calculated directly from:

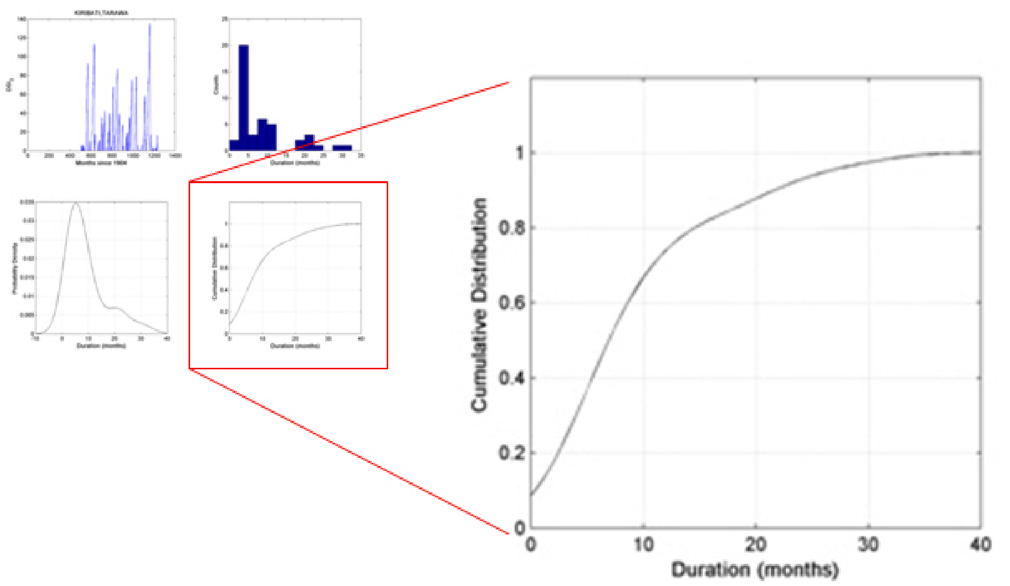
1. consideration of the cumulative distribution plots (bottom right-hand graph) for each location given in Appendix 6; and

2. drought occurrence parameter, θ, given in Table 4.

As an example, what is the probability of a drought at Tarawa having a duration less than 10 months and what is approximately the AEP of a drought with a duration of 10 months?

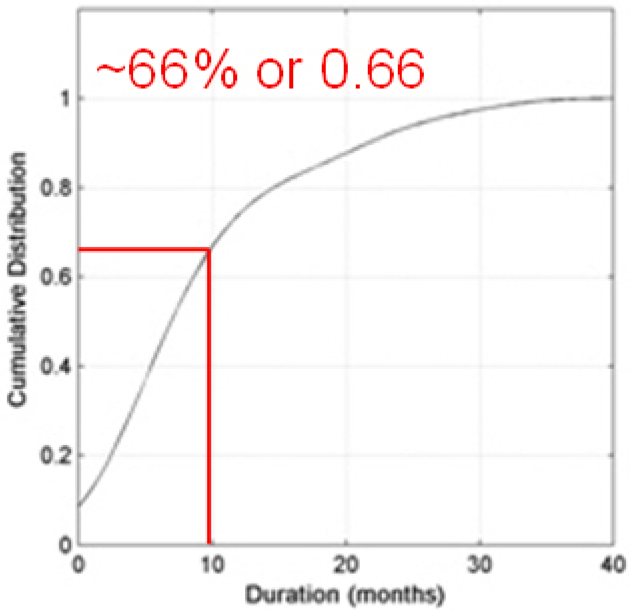
For the first part of this question:

- Find the corresponding cumulative distribution plot for Tarawa in Appendix 6.



- For a 10 month duration on the x-axis, find where this intersects with the cumulative distribution curve.

- Read off the corresponding cumulative distribution.



- The probability of a drought at Tarawa having a duration of 10 months or less is 0.66 (i.e., there is a 66% chance that a drought at Tarawa will have a duration of 10 months or less).

To calculate the annual exceedance probability of a 10 month duration drought:

- Calculate the probability of a drought having a duration of 10 months or less, i.e., as above, Prob. = 0.66.

- Find the drought occurrence parameter, θ, from Table 4 for Tarawa.

		ARI (years) / AEP (%)						
		2	5	10	20	50	75	100
Site	θ	50%	20%	10%	5%	2%	1.3%	1%
Washington Is	1.05	6	10	13	18	20	21	22
Fanning Is	0.91	5	11	15	19	24	27	29
Christmas Is	1.02	6	10	14	16	18	19	19
Banaba	0.63	3	13	18	22	32	36	37
Butaritari	0.90	5	11	15	20	27	31	33
Makin	0.94	5	12	16	20	23	24	25
Marakei	0.77	4	12	17	20	24	25	26
Abaiang	0.68	3	11	17	25	35	37	38
Tarawa	0.75	4	12	19	24	30	31	32
Maiana	0.68	5	12	16	24	32	34	35

- For Tarawa, the drought occurrence parameter, θ, is 0.75.
- Annual exceedance probability (AEP) = (θ x (1-Prob)).
- AEP = 0.75 x (1-0.66) = 0.255 or 25.5%.
- That is, on average, there is a 25.5% change of there being a drought of 10 months duration in any one year.
- Alternatively this could be expressed as: on average a drought of 10 months duration would be expected to occur about once every 3.9 years (1/0.255 = 3.9 years).

4.7.3 Joint frequency of drought duration and intensity – worked example

To obtain the recurrence interval or AEP of the joint frequency of drought duration and intensity for a rainfall site in Kiribati, the figures in Appendix 7 are used:

1. Go to the relevant diagram in Appendix 7 for the location of interest.
2. For the given drought duration given by the x-axis in the left hand diagram, select or interpolate a given drought intensity (i_o) from within the body of the diagram.
3. At the point of intersection of the duration and intensity, read from the y-axis the cumulative distribution value.

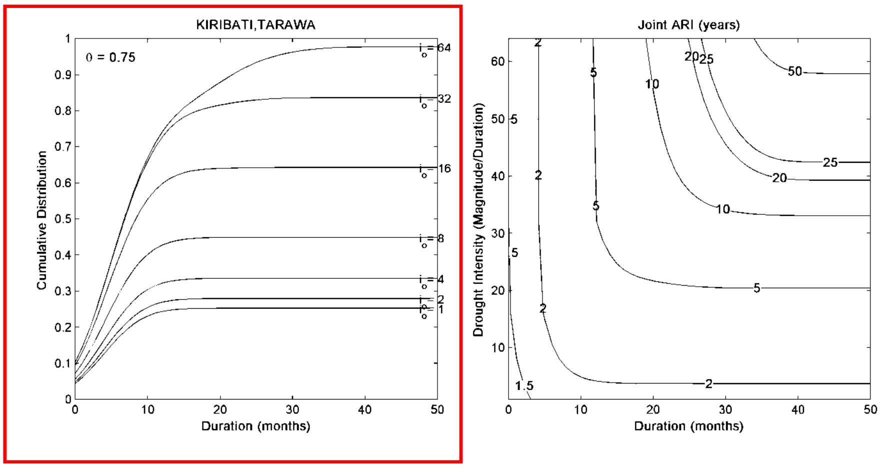
4. The cumulative distribution in conjunction with the drought occurrence parameter, θ, (Table 4) is used to evaluate the joint recurrence interval between drought duration and intensity. Note: These are also provided by the right hand diagrams in the figures and method is given in step 5.

5. From the right hand diagrams for the location of interest, selected the required drought duration on the x-axis and the required drought intensity from the y-axis. The point of intersection of these two values provides the joint average recurrence interval in years.

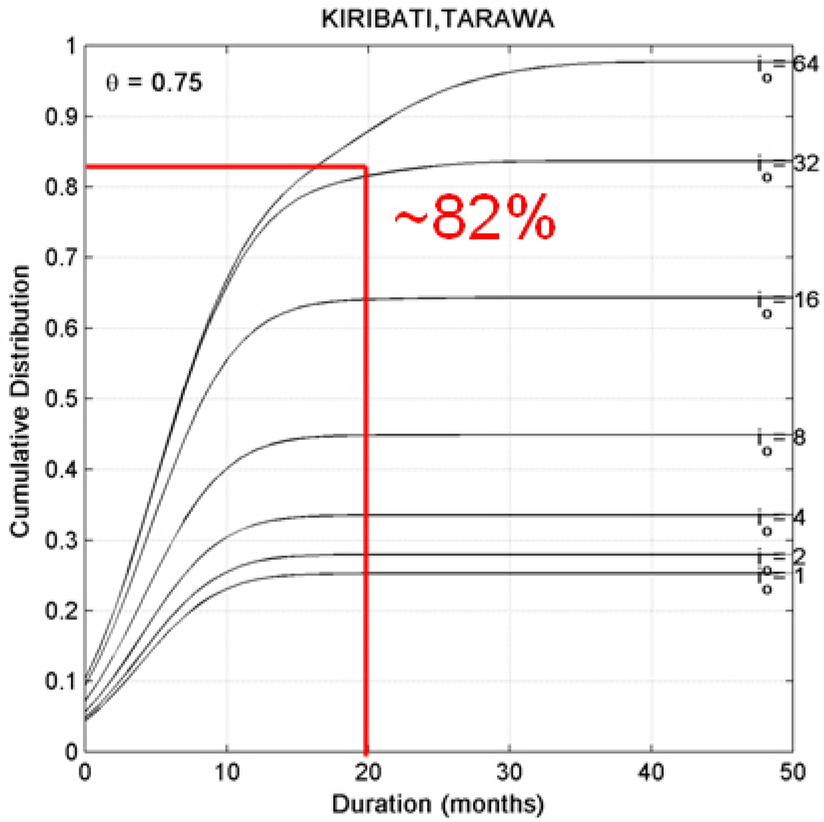
As an example, approximately what percentage of droughts with an intensity of 40 persist for less than 20 months at Tarawa, and what is the approximate AEP for a drought of this severity and duration?

For the first part of this question:

- Find the corresponding cumulative distribution plot for Tarawa in Appendix 7.



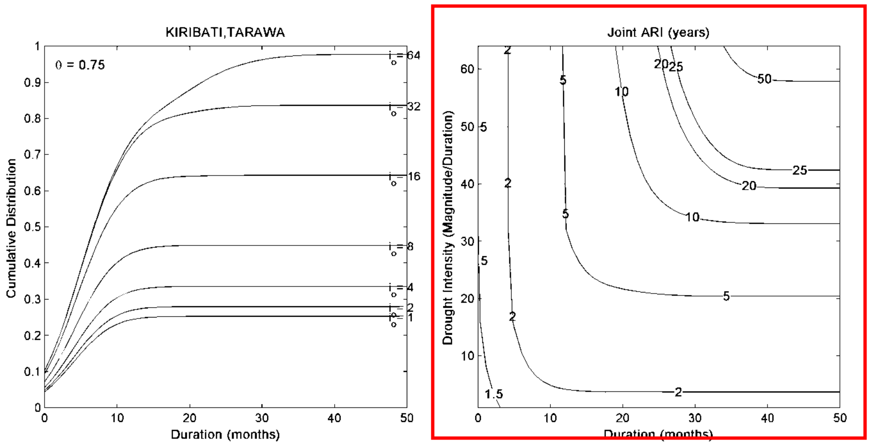
- For a duration of 20 months (x-axis), and for an intensity (i_o) of 40 (interpolate between the lines of intensities of 32 and 64) estimate the cumulative distribution (y-axis).



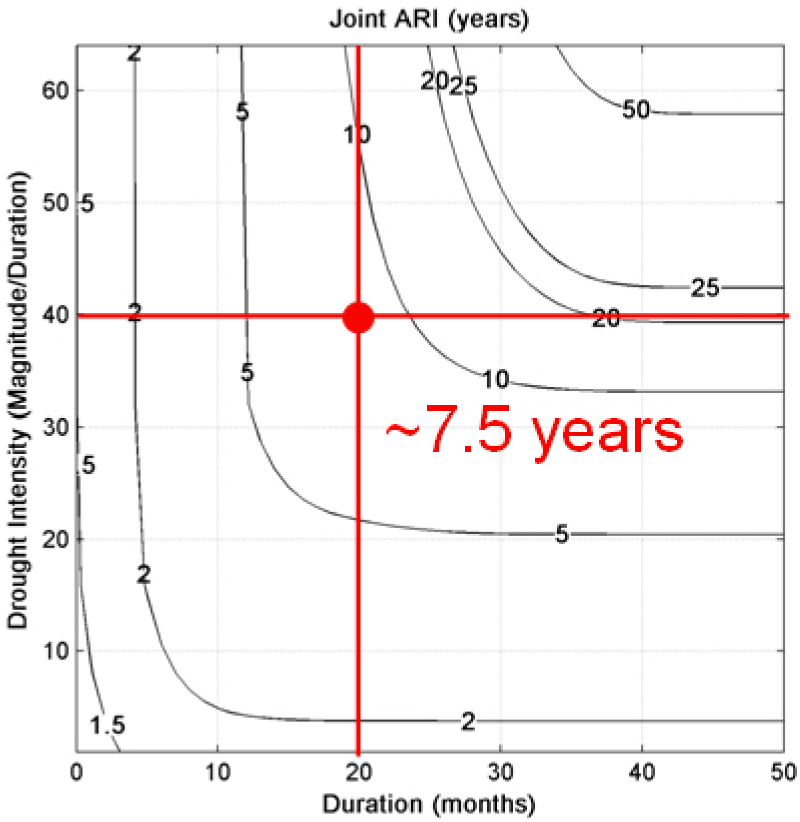
- Approximately 82% of droughts with an intensity of 40 persist for 20 months or less on Tarawa.

To calculate the annual exceedance probability (AEP) for this intensity and duration drought, either:

- Use the drought occurrence parameter (θ) from Table 4 and the equation outlined in Section 4.7.2 above.
  - For Tarawa, the drought occurrence parameter, θ, is 0.75.
  - Annual exceedance probability (AEP) = (θ x (1-Prob)).
  - AEP = 0.75 x (1-0.82) = 0.135 or 13.5%.
  - That is, on average, there is a 13.5% change of there being a drought of 20 months duration and intensity of 40 occurring in any one year.
- Use the right hand plots for the location of interest in Appendix 7:



- For a duration of 20 months (x-axis) and intensity of 40 (y-axis), find where the intersection occurs.



- For the point of the intersection, interpolate between the average recurrence interval (ARI) contours. The intersection gives an approximate ARI = 7.5 years.

- The annual exceedance probability (AEP) = 1/7.5 years = 0.133 (13.3%).