Mapping the river drought-indices in west Sumatra

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Abstract. The smallest magnitudes from a series of daily average-streamflows every month are selected to form a new series of data called a series of monthly minima from daily average-streamflows or then just simply called the monthly minimum-streamflows. The present study uses these monthly minimum-streamflows to determine a drought index in terms of duration and deficit streamflows of successive drought in every watershed in West Sumatra Province. Both terms of drought index are determined by using the theory of runs with a 5-year average-period. So far, we successfully collect series of the daily average-streamflows for 19 watersheds with a minimum length of 20 years. The resulting indices are then mapped using the geographical information system ArcGIS. The drought indices are expressed in 4 levels of drought: normal (green), mild (blue), moderate (yellow) and severe (red). The study results show that the river or watershed with the longest drought-duration is Batang Anai, *i.e.* 33 months (severe level), with a cumulative deficit-streamflows of 143.26 m^3/s. The river with the shortest drought-duration is Batang Siat, *i.e.* 11 months (mild level), with a cumulative deficit-streamflows of 44.64 m^3/s. The average drought-duration for all corresponding rivers is 20 months (mild level) with a cumulative deficit-streamflows of 131.57 m^3/s.

1 Introduction

Drought is one type of natural disaster that occurs in the dry season. Drought is a lack of rainfall than usual or a normal state, which occurs prolonged that could be along one session or more. As a result, a river in that watershed is unable to meet the water demand [1]. The longer dry season, the longer drought will be. These erratic natural events make it difficult to predict when and how long the drought happen. One way to anticipate the drought effects in a watershed is to determine its drought index.

In 2004, the Indonesian Public Work Department defined that a drought index is a single value to describe the severity of drought, in the forms of the longest drought-duration and the largest amount of droughts with a certain average-period. The resulting drought-indices (drought duration and amount) then can be applied: in the plan stage such as determining a reservoir capacity; in the operation stage such as irrigating in the dry season; and in the mitigation and reduction of the drought effects [1].

In 2016, World Meteorological Organization (WMO) and Global Water Partnership (GWP) listed some the most commonly used drought indicators/indices that are being applied across drought-prone regions, with the goal of advancing monitoring, early warning and information delivery systems in support of risk-based drought management policies and preparedness plans. The WMO is a specialised agency in the United Nations for the state and behaviour of the earth's atmosphere, its interaction with the land and oceans, weather and climate. The indicators and indices listed are categorised by the type and ease of use, and grouped into the classifications of: meteorology, soil moisture, hydrology, remote sensing, and composite or modelled. In the classification of hydrology, there are Standardised Streamflow Index (SSFI), Streamflow Drought Index (SDI), Surface Water Supply Index (SWSI), Aggregate Dryness Index (ADI) and Standardised Snowmelt and Rain Index (SSRI) that are using streamflow data as input parameters [2]. However, the theory of runs, one of the popular drought index [3-8], is not listed by WMO & GWP.

In the run theory, the drought in a watershed is when a minimum streamflow in a certain month being smaller than the average of minimum streamflows of the corresponding month for the certain period. In the present study, we determine the river drought-indices in West Sumatra Province (Fig. 1) using the theory of runs. We successfully collect series of the daily average-streamflows for 19 watersheds with a minimum length of 20 years. The resulting indices are then mapped using the geographical information system ArcGIS.

Fig. 1. Location of West Sumatra (red) in Indonesia [9].

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2 Methodology

We collect series of the daily average-streamflows for 19 watersheds. The smallest magnitudes from each series every month are selected to form a new series of data called a series of monthly minima from daily average-streamflows or then just simply called the monthly minimum-streamflows $Q_{m,t}$ in which Q indicates monthly minimum-streamflow, m indicates the certain month, and t indicates the certain year. In the run theory, the length of data must be a multiple of 5 years. Now, the monthly minimum-streamflows $Q_{m,t}$ are sorted out by year, from the earliest year to the recent year. The arithmetic average of $Q_{m,t}$ for every month m along n year is Q_m and is determined by

$$Q_m = \frac{1}{n}\sum_{t=1}^{n} Q_{m,t} \tag{1}$$

If we have a series of data for 20-year long from year 1992 to 2012, set $n = 20, t = 1$ for year 1992 and $t = 20$ for year 2012, $m = 1$ for month January and $m = 12$ for month December. For example, please consider Batang Palangki streamflows in Table 1. The arithmetic average of $Q_{m,t}$ for month January is

$$Q_1 = \frac{1}{20}\sum_{t=1}^{20} Q_{1,t} = \frac{1}{20}\left(Q_{1,1} + Q_{1,2} + \cdots + Q_{1,20}\right)$$
$$Q_1 = \frac{1}{20}(29.4 + 26.1 + \cdots + 25.5) = 23.12$$

So, the average streamflow in January for 20 years is 23.12 m^3/s. The average streamflows for other months can be seen in Table 1.

Table 1. The monthly minimum-streamflows $Q_{m,t}$ of Batang Palangki.

Year	Month (*m*)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
t	1	2	3	4	5	6	7	8	9	10	11	12
1992 = 1	29.40	22.70	22.70	22.10	24.40	13.70	13.70	7.92	6.24	9.36	13.30	36.90
1993 = 2	26.10	16.10	17.60	9.73	13.90	8.46	11.00	8.89	7.20	15.60	37.50	15.20
1994 = 3	17.30	17.30	17.30	18.10	19.80	12.70	8.70	6.30	6.60	7.50	8.10	9.00
1995 = 4	26.90	16.20	25.80	30.20	20.80	20.40	15.60	15.60	14.40	16.20	10.40	11.70
1996 = 5	14.40	16.80	24.40	30.20	19.10	12.00	12.30	12.30	13.20	13.80	12.30	13.20
1997 = 6	11.70	7.02	7.02	12.30	11.70	7.65	8.49	7.23	7.02	7.02	7.02	9.54
1998 = 7	29.10	16.80	10.20	12.30	13.80	12.60	10.40	12.00	25.90	13.50	10.60	9.96
1999 = 8	10.20	10.20	8.07	5.34	7.44	9.54	6.60	6.60	9.75	15.00	16.80	14.40
2000 = 9	25.40	17.30	12.30	8.90	6.39	8.49	7.23	8.91	7.86	8.12	8.72	15.60
2001 = 10	12.90	14.70	8.91	9.33	14.10	10.80	9.33	7.65	6.81	7.23	7.44	7.65
2002 = 11	9.96	12.90	12.60	28.00	20.90	12.00	10.60	11.40	13.50	17.70	19.50	29.60
2004 = 12	14.27	18.02	11.48	19.61	21.24	9.22	8.92	6.86	7.14	8.61	33.33	25.94
2005 = 13	36.75	22.07	29.09	22.07	33.33	19.61	15.73	17.63	13.91	17.25	24.19	23.33
2006 = 14	23.76	35.27	37.75	34.78	34.78	25.06	17.25	21.24	26.38	26.38	31.89	54.36
2007 = 15	63.11	63.11	46.07	43.94	31.42	39.78	26.38	23.76	22.91	27.27	39.78	30.02
2008 = 16	19.61	18.41	18.41	22.07	14.63	30.48	30.95	32.85	58.39	57.23	45.00	37.75
2009 = 17	39.78	38.25	38.25	41.84	38.76	35.27	38.25	34.78	39.27	37.75	51.55	47.69
2010 = 18	22.60	8.27	28.40	42.80	16.40	12.70	21.70	19.00	27.50	20.60	22.60	24.20
2011 = 19	3.34	5.64	5.03	5.95	9.16	5.96	3.75	2.76	2.40	1.89	5.10	4.81
2012 = 20	25.80	28.60	23.60	24.70	29.20	35.60	26.30	22.00	21.70	52.40	62.50	62.10
n	20	20	20	20	20	20	20	20	20	20	20	20
Sum	462.38	405.67	405.00	444.25	401.24	342.02	303.18	285.67	338.07	380.41	467.61	482.95
Ave, Q_m	23.12	20.28	20.25	22.21	20.06	17.10	15.16	14.28	16.90	19.02	23.38	24.15

Surplus and deficit streamflows $D_{m,t}$ are determined using formula

$$D_{m,t} = Q_{m,t} - Q_m \tag{2}$$

For example, the arithmetic average of Batang Palangki streamflows for month January $Q_m = Q_1$ along 20-year period is 23.12 m^3/s and the monthly minimum-streamflows in January 1992 $Q_{m,t} = Q_{1,1}$ is 29.40 m^3/s and in January 1996 $Q_{m,t} = Q_{1,5}$ is 14.40 m^3/s. It means that Batang Palangki surplus 6.28 m^3/s (*i.e.* $D_{1,1} = 29.40 - 23.12$) in January 1992 and deficit 8.72 m^3/s (*i.e.* $D_{1,5} = 14.40 - 23.12$) in January 1996. Both surplus and deficit values are called as run values. The plus sign indicates surplus and negative one indicates deficit (Table 2).

Table 2. The surplus and deficit streamflows $D_{m,t}$ or the run values of Batang Palangki.

Year	Month (*m*)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
t	1	2	3	4	5	6	7	8	9	10	11	12
1992 = 1	6.28	2.42	2.45	-0.11	4.34	-3.40	-1.46	-6.36	-10.66	-9.66	-10.08	12.75
1993 = 2	2.98	-4.18	-2.65	-12.48	-6.16	-8.64	-4.16	-5.39	-9.70	-3.42	14.12	-8.95
1994 = 3	-5.82	-2.98	-2.95	-4.11	-0.26	-4.40	-6.46	-7.98	-10.30	-11.52	-15.28	-15.15
1995 = 4	3.78	-4.08	5.55	7.99	0.74	3.30	0.44	1.32	-2.50	-2.82	-12.98	-12.45
1996 = 5	-8.72	-3.48	4.15	7.99	-0.96	-5.10	-2.86	-1.98	-3.70	-5.22	-11.08	-10.95
1997 = 6	-11.42	-13.26	-13.23	-9.91	-8.36	-9.45	-6.67	-7.05	-9.88	-12.00	-16.36	-14.61
1998 = 7	5.98	-3.48	-10.05	-9.91	-6.26	-4.50	-4.76	-2.28	9.00	-5.52	-12.78	-14.19
1999 = 8	-12.92	-10.08	-12.18	-16.87	-12.62	-7.56	-8.56	-7.68	-7.15	-4.02	-6.58	-9.75
2000 = 9	2.28	-2.98	-7.95	-13.31	-13.67	-8.61	-7.93	-5.37	-9.04	-10.90	-14.66	-8.55
2001 = 10	-10.22	-5.58	-11.34	-12.88	-5.96	-6.30	-5.83	-6.63	-10.09	-11.79	-15.94	-16.50
2002 = 11	-13.16	-7.38	-7.65	5.79	0.84	-5.10	-4.56	-2.88	-3.40	-1.32	-3.88	5.45
2004 = 12	-8.85	-2.26	-8.77	-2.61	1.17	-7.88	-6.24	-7.43	-9.77	-10.41	9.95	1.79
2005 = 13	13.63	1.78	8.84	-0.15	13.26	2.51	0.57	3.35	-3.00	-1.77	0.81	-0.81
2006 = 14	0.64	14.99	17.50	12.57	14.72	7.96	2.09	6.95	9.48	7.36	8.51	30.21
2007 = 15	39.99	42.83	25.82	21.72	11.36	22.68	11.22	9.48	6.01	8.25	16.40	5.87
2008 = 16	-3.51	-1.87	-1.83	-0.15	-5.43	13.38	15.79	18.56	41.49	38.21	21.62	13.60
2009 = 17	16.66	17.97	18.00	19.63	18.70	18.17	23.10	20.50	22.36	18.73	28.16	23.54
2010 = 18	-0.52	-12.01	8.15	20.59	-3.66	-4.40	6.54	4.72	10.60	1.58	-0.78	0.05
2011 = 19	-19.78	-14.64	-15.22	-16.26	-10.90	-11.14	-11.41	-11.52	-14.50	-17.13	-18.28	-19.34
2012 = 20	2.68	8.32	3.35	2.49	9.14	18.50	11.14	7.72	4.80	33.38	39.12	37.95

All the values of surplus streamflow in Table 2 are replaced by zero as indicators, however the values of a deficit streamflow are replaced by the indicator in previous month plus 1. The resulting indicators in the deficit months indicate the duration of consecutive drought L_t up to the months (Table 3). As shown in Table 3 that the longest consecutive drought $L_{t\ max}$ in the certain period is shown by the biggest indicator number in the corresponding period. The Batang Palangki experienced the drought duration for 18.5 consecutive months in 5-year average-period.

Table 3. The drought duration L_t of Batang Palangki.

Year	Month (*m*)												L_{tmax} (months)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
t	1	2	3	4	5	6	7	8	9	10	11	12	
1992 = 1	0	0	0	**1**	0	**1**	**2**	**3**	**4**	**5**	**6**	0	**13**
1993 = 2	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	0	**1**	
1994 = 3	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	
1995 = 4	0	**1**	0	0	0	0	0	0	**1**	**2**	**3**	**4**	
1996 = 5	**5**	**6**	0	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
1997 = 6	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**23**
1998 = 7	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	0	**1**	**2**	**3**	
1999 = 8	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	
2000 = 9	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	
2001 = 10	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	
2002 = 11	**24**	**25**	**26**	0	0	**1**	**2**	**3**	**4**	**5**	**6**	0	**26**
2004 = 12	**1**	**2**	**3**	**4**	0	**1**	**2**	**3**	**4**	**5**	0	0	
2005 = 13	0	0	0	**1**	0	0	0	0	**1**	**2**	0	**1**	
2006 = 14	0	0	0	0	0	0	0	0	0	0	0	0	
2007 = 15	0	0	0	0	0	0	0	0	0	0	0	0	
2008 = 16	**1**	**2**	**3**	**4**	**5**	0	0	0	0	0	0	0	**12**
2009 = 17	0	0	0	0	0	0	0	0	0	0	0	0	
2010 = 18	**1**	**2**	0	0	**1**	**2**	0	0	0	0	**1**	0	
2011 = 19	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
2012 = 20	0	0	0	0	0	0	0	0	0	0	0	0	
									Average Drought Duration (months) =				**18.5**

The sum of deficit streamflows is determined by summing up all consecutive deficit streamflows. For example, deficit flows in June 1992 is 3.40 m^3/s, in July is 1.46 m^3/s, in August is 6.36 m^3/s (see Table 2), and so the cumulative deficit flows up to August 1992 are $3.40 + 1.46 + 6.36 = 11.2$ m^3/s (see Table 4). As shown in Table 4 that the Batang Palangki experienced the most severe drought for 187.2 m^3/s in 5-year average-period.

Table 4. The cumulative drought (m^3/s).

Year t	Jan 1	Feb 2	Mar 3	Apr 4	May 5	Jun 6	Jul 7	Aug 8	Sep 9	Oct 10	Nov 11	Dec 12	Q_{tmax} (m^3/s)
1992 = 1	0.00	0.00	0.00	**-0.11**	0.00	**-3.40**	**-4.86**	**-11.22**	**-21.89**	**-31.55**	**-41.63**	0.00	
1993 = 2	0.00	**-4.18**	**-6.83**	**-19.32**	**-25.48**	**-34.12**	**-38.28**	**-43.67**	**-53.38**	**-56.80**	0.00	**-8.95**	
1994 = 3	**-14.77**	**-17.75**	**-20.70**	**-24.81**	**-25.07**	**-29.47**	**-35.93**	**-43.92**	**-54.22**	**-65.74**	**-81.02**	**-96.17**	**96.17**
1995 = 4	0.00	**-4.08**	0.00	0.00	0.00	0.00	0.00	0.00	**-2.50**	**-5.32**	**-18.30**	**-30.75**	
1996 = 5	**-39.47**	**-42.95**	0.00	0.00	**-0.96**	**-6.06**	**-8.92**	**-10.91**	**-14.61**	**-19.83**	**-30.91**	**-41.86**	
1997 = 6	**-53.28**	**-66.54**	**-79.77**	**-89.68**	**-98.04**	**-107.50**	**-114.16**	**-121.22**	**-131.10**	**-143.10**	**-159.46**	**-174.07**	
1998 = 7	0.00	**-3.48**	**-13.53**	**-23.45**	**-29.71**	**-34.21**	**-38.97**	**-41.25**	0.00	**-5.52**	**-18.30**	**-32.49**	
1999 = 8	**-45.41**	**-55.49**	**-67.67**	**-84.54**	**-97.17**	**-104.73**	**-113.29**	**-120.97**	**-128.12**	**-132.14**	**-138.72**	**-148.47**	**222.06**
2000 = 9	0.00	**-2.98**	**-10.93**	**-24.25**	**-37.92**	**-46.53**	**-54.46**	**-59.83**	**-68.88**	**-79.78**	**-94.44**	**-102.98**	
2001 = 10	**-113.20**	**-118.79**	**-130.13**	**-143.01**	**-148.97**	**-155.27**	**-161.10**	**-167.73**	**-177.83**	**-189.62**	**-205.56**	**-222.06**	
2002 = 11	**-235.22**	**-242.60**	**-250.25**	0.00	0.00	**-5.10**	**-9.66**	**-12.54**	**-15.95**	**-17.27**	**-21.15**	0.00	
2004 = 12	**-8.85**	**-11.11**	**-19.88**	**-22.48**	0.00	**-7.88**	**-14.12**	**-21.55**	**-31.31**	**-41.72**	0.00	0.00	
2005 = 13	0.00	0.00	0.00	**-0.15**	0.00	0.00	0.00	0.00	**-3.00**	**-4.77**	0.00	**-0.81**	**250.25**
2006 = 14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
2007 = 15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
2008 = 16	**-3.51**	**-5.38**	**-7.22**	**-7.36**	**-12.79**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
2009 = 17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
2010 = 18	**-0.52**	**-12.53**	0.00	0.00	**-3.66**	**-8.06**	0.00	0.00	0.00	0.00	**-0.78**	0.00	**180.13**
2011 = 19	**-19.78**	**-34.42**	**-49.64**	**-65.90**	**-76.81**	**-87.95**	**-99.36**	**-110.88**	**-125.38**	**-142.51**	**-160.80**	**-180.13**	
2012 = 20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
												Average Cumulative Drought (m^3/s) =	**187.2**

3 Results and Discussions

Drought indices for other rivers are determined as done for Batang Palangki. They are expressed in terms of the duration of consecutive drought and in terms of the deficit streamflows of successive drought for a 5-year average-period. The summary can be seen in Table 5. From the table can be seen that Batang Anai experienced the longest drought-duration *i.e.* for 33 consecutive months in 5-year average-period, and Batang Siat experienced the shortest drought-duration, *i.e.* for 11 consecutive months in 5-year average-period. Even though Batang Hari experienced drought for only 16 consecutive months, this watershed experienced deficit flow of 972.19 m^3/s compared to Batang Anai with deficit flow of 143.26 m^3/s for 33 months. Batang Kalulutan experienced drought longer than Batang Kiat, however Batang Kalulutan experienced the smallest deficit flow *i.e.* 12.99 m^3/s with 22 consecutive months compared to Batang Kiat is 44.64 m^3/s with 11 consecutive months.

Table 5. The recapitulation of the duration of consecutive drought (month) and the deficit streamflows of consecutive drought (m^3/s).

No	Watershed	The duration of censecutive drought: L_t (months)	Level	The deficit streamflows of consecutive drought: D_t (m^3/s)	Level
1	Batang Anai	33		143.26	
2	Batang Selo	30		49.53	49.53
3	Batang Ombilin	30		302.18	
4	Batang Lampasi	28		22.99	22.99
5	Batang Sumani	25		105.60	
6	Batang Sinamar	23		179.77	
7	Batang Kalulutan	22		12.99	12.99
8	Batang Naras	22		34.20	34.20
9	Batang Palangki	19		185.71	
10	Batang Masang	18		129.99	
11	Batang Agam	17		22.75	22.75
12	Batang Hari	16		972.91	
13	Batang Kenaikan	14		72.04	72.04
14	Batang Mangau	14		55.61	55.61
15	Batang Sukam	14		46.21	46.21
16	Batang Tongar	13		65.30	65.30
17	Batang Lembang	13		16.82	16.82
18	Batang Air Dingin	12	12	37.26	37.26
19	Batang Siat	11	11	44.64	44.64
	Maxima	**33**		**972.91**	
	Minima	**12**	12	**12.99**	12.99
	Average	**20**	11	**131.57**	12.99

To map all the river drought-indices considered in the present study, the indices should be expressed in terms of drought level. So far, however we couldn't find any reference saying what the criteria of the drought level are. The criteria should have relation to both the duration and deficit streamflows of consecutive drought. Based on Table 5, however, we can propose that the drought level in terms of duration of consecutive drought as follow: normal level (green) for 0 to 2 months; mild level (blue) for 3 to 12 months; moderate level (yellow) for 13 to 24 months; and severe level (red) for 25 months or longer. The indices of 19 watersheds are then mapped using ArcGIS as shown in Fig. 2. From the figure can be seen that there are 5 watersheds, *i.e.* Batang Anai, Batang Selo, Batang Ombilin, Batang Lampasi and Batang Sumani, which are at severe level and coloured as red. The drought indices in terms of deficit streamflows should follow those in terms of duration. Due to the variation in sizes of watershed, however, a watershed with a longer drought-duration is not always to be that with a biggest deficit-flow. Consequently, we propose the drought level in terms of deficit streamflows of consecutive drought as follow: normal level (green) for 0 to 5 m^3/s; mild level (blue) for 6 to 100 m^3/s; moderate level (yellow) for 101 to 200 m^3/s; and severe level (red) for 201 m^3/s or larger as shown in Fig. 3. This figure shows that there are only 2 watersheds at severe level, *i.e.* Batang Hari and Batang Ombilin.

4 Conclusions

The present study successfully maps the river drought-indices in West Sumatra in terms of duration and deficit streamflows of successive drought. The corresponding results show that the river or watershed with the longest drought-duration is Batang Anai, *i.e.* 33 months (at severe level), with a cumulative deficit-streamflows of 143.26 m^3/s. The river with the shortest drought-duration is Batang Siat, *i.e.* 11 months (at mild level), with a cumulative deficit-streamflows of 44.64 m^3/s. The average drought-duration for all corresponding rivers is 20 months (at mild level) with a cumulative deficit-streamflows of 131.57 m3/s.

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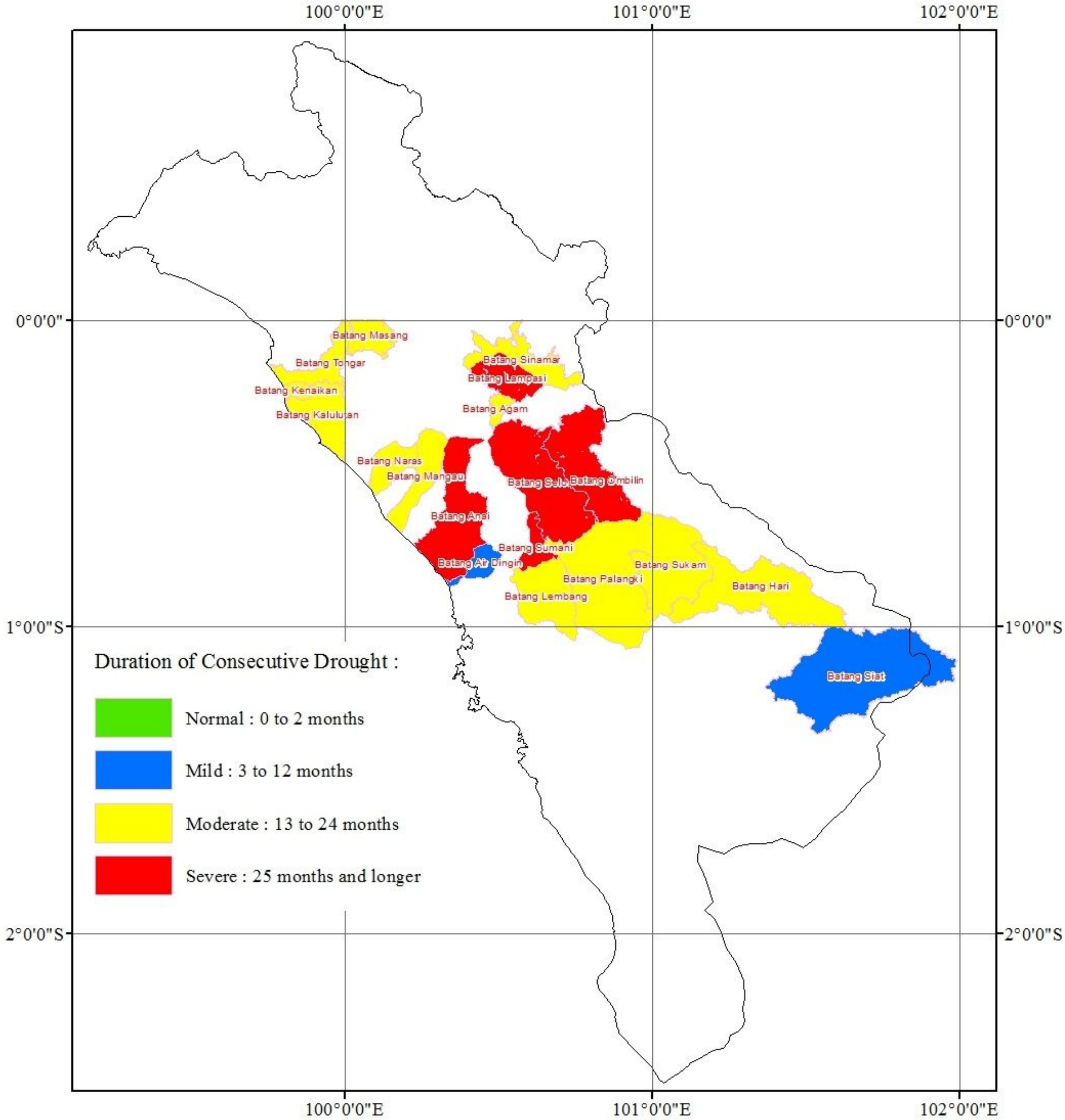

Fig. 2. River drought-indices in terms of duration of consecutive drought.

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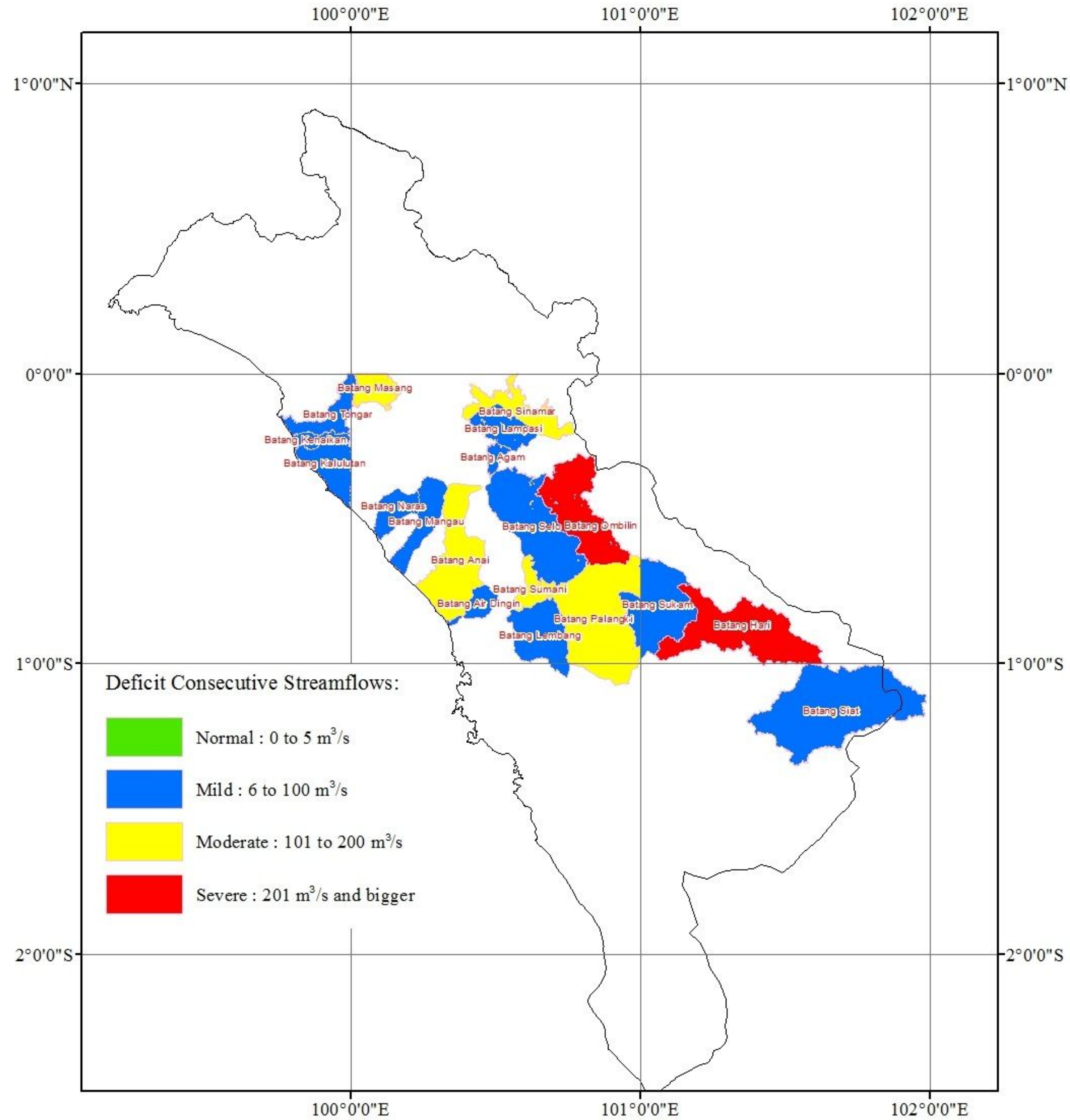

Fig. 3. River drought-indices in terms of deficit streamflows of consecutive drought.