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LARGE IMPACTS OF INDO-PACIFIC CLIMATE MODES ON THE EXTREME STREAMFLOWS OF CITARUM RIVER IN INDONESIA

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Large impacts of climate variations modes are found on the extreme stream-flow events of Citarum River derived from the daily stream-flows at the Nanjung gauge station. Extreme events are identified based on their persistent flow for 5 or more days in DJF and MAM seasons when the seasonal mean stream-flows are high. During DJF the positive phases of the Indian Ocean Dipole (IOD) are associated with extremely low-stream-flow events. Except for one independent IOD events, all low-stream-flow events related to positive IOD events were also associated with El Niño events. However, none of the low-stream-flow events were uniquely associated with El Niño events independent of IOD events in the Indian Ocean. In addition, a few rare low-stream-flow events in DJF associated with La Niña are also accompanied by positive IOD. Therefore, the positive IOD has overwhelmingly negative impacts on stream-flows of Citarum River. The extreme events of high-stream-flows were mostly related to La Niña conditions during DJF and MAM. Some of the extreme high-flow events were also associated with the negative phases of IOD with a characteristically opposite conditions to that of the positive phase. Interestingly, La Niña Modokis dominantly influenced the low-stream-flow events when cold anomalies of sea surface temperature flanked the coast of Java-Sumatra in MAM.

***Key Words :** IOD, El Niño Modoki,La Niña Modoki, Streamflows, Citarum river. Climate variability*

1. INTRODUCTION

The Citarum river basin is an important water resource in Indonesia. The river has a vital role in the economic development and prosperity of the people in West Java Province and Jakarta City. It has been exploited to support agriculture, fisheries, public water supply and industry, and generation of hydroelectric power [1]. There are three reservoirs (Saguling, Cirata and Jatiluhur) which are built to regulate flows, provide hydro power, and manage water for irrigation, industrial and residential uses. There are two protected forest areas in the upper Citarum catchment, which cover nearly 30% of its total area. The rest of the catchment is used for other activities, such as agriculture, residential and industrial activities. This region is one of the fastest growing and densely populated regions of Indonesia. In the past three decades, Bandung and Jakarta has experienced considerable rapid growth in industrial development and in urbanization. As such, large number of irrigated paddy fields and dry crops land in Bandung have been converted into housing complexes as well as business and industrial areas [2]. The land use changes in the catchment have a detrimental impact on water quality and availability. Water inflow into the reservoirs has been decreasing and the systems reportedly failed to meet water needs [3]. The stream-flows, unlike the rainfall, are affected by morphological and anthropogenic factors including soil and forestry recharge, sediment deposit, topography and land-use changes besides rainfall [4]. Therefore, it is important to understand the extreme events of river stream-flows through adequate scientific analysis. The Citarum River basin is mainly dependent on the seasonal monsoon rainfall from October to May. The warm pool near Indonesia and the associated ascending branch of Walker circulation play crucial roles in determining rainfall variability in the Maritime Continent [5].

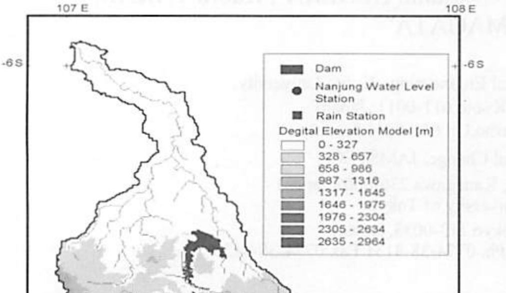


Fig. 1 The Citarum river catchment with Nanjung gauge station and three reservoirs, the Saguling, Cirata and Jatiluhar (Juanda) from upper to lower stream respectively.

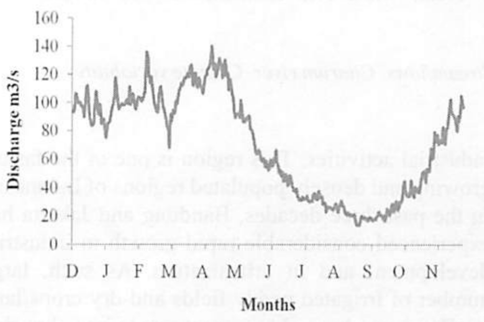
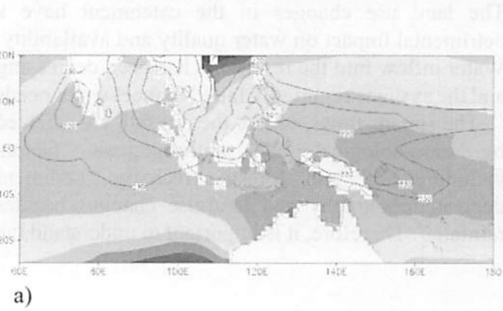


Fig.2 The discharges climatology of the Nanjung station.



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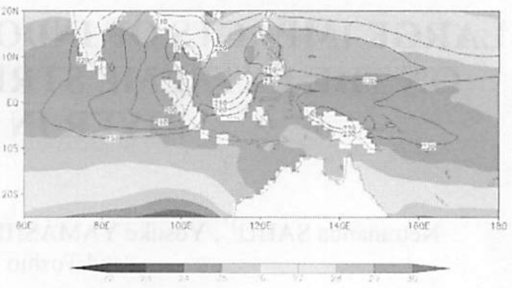


b)

Fig. 3 Seasonal mean SST (shaded) and OLR are shown for a) December-February and b) March-May. OLR contours above 230 Wm^{-2} are suppressed.

This study attempts to understand the regional manifestation of Indo-Pacific climate impacts. While it is well-known that the Indo-Pacific climate largely influences the large-scale phenomenon such as monsoon, it is unclear how such large-scale impacts manifest regionally, for example in terms of the river discharges as we studied here. Therefore, the relationship between river stream-flow and climate variation are very important though the latter factor has a direct impact on rainfall variability. To reduce the impact of anthropogenic activities such as dams/reservoirs or any artificial diversions on the streamflow, we select the Nanjung gauge station (**Fig. 1**) for our study. Apip *et al* [6] have observed the retention time at Nanjung stations around 24 hours. In this study we attempt to examine the IOD, ENSO and ENSO Modoki impact on the river stream-flow variations of Indonesia for the first time.

2.DATA AND METHODS

Daily climatology and anomalies of river stream-flow are computed from the 35 (1974-2008) year's data at the Nanjung gauge stations of the Citarum River. Extremely high and low stream-flow events were obseved based on a standard deviation threshold; 1.5σ and -1σ are set as threshold for extreme high and low stream-flows, respectively [7]. Continuously high and low values for above five days are then combined to formulate the total number of extreme events. The dipole mode index (DMI) is derived from SST anomalies by taking difference between the western (50°E-70°E, 10°S-10°N) and eastern (90°E-110°E, 10°S-Eq) tropical Indian Ocean [8]. The Nino3 index is derived by taking area average of SST over eastern Pacific (150°W-90°W, 5°S-5°N). Zonal wind data are obtained from NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) data base [9].

The other major dataset used in this study is the global coverage NOAA interpolated of daily averages of outgoing longwave radiation anomalies (here after OLR) data on a 2.5° × 2.5° grid at standard pressure levels from 1 January 1979 to 31 December 2008 [10]. SST anomalies are used from the daily OISST analysis version 2 AVHRR-AMSR (Advanced Very High Resolution Radiometer-Advanced Microwave Scanning Radiometer) products from NCDC (National Climate Data Center) [11].

3 STREAMFLOW CHARECTERSTICS

The daily climatology (**Fig. 2**) of the Citarum stream-flows shows higher seasonal flows during the months of December to May. There is very less stream-flow in June-August. Therefore, for its obvious impacts on the ecosystem and human population, we examined the stream-flow variability during December-May (Table 1 and 2). The seasonal streamflow patterns at Nanjung station and rainfall patterns over Java are very similar [12), 13)]. The coherent patterns of SST(shaded) and OLR (contour) depict the seasonal variations of rainfall over Sumatra region are shown for DJF (**Fig. 3a**) and MAM (**Fig. 3b**) seasons.

Before going to analyse the climate variability impacts, here we define the basic charaterstics of the climate variability which influenced the study region. A positive IOD (here after pIOD) phenomenon is characterized by cooler than normal water in the tropical eastern Indian Ocean and warmer than normal water in the tropical western Indian Ocean [8]. It brings heavy rainfall over the east Africa, India, Bangladesh and Vietnam and severe droughts/forest fires over Indonesia, Australia and dry as well as hot summer in Europe, Japan, Korea and East China [8]. A negative IOD (here after nIOD) is characterized just reverse of pIOD. The nIOD sea surface temperature pattern often results in an increase of rainfall over parts of Australia and Indonesia whereas droughts in East of Africa and Indian Subcontinent [8].

The seasonal circulations are modified by IOD,which play a significant role in modulating seasonal rainfall over Indonesia [14)]. Therefore, it is reasonable to expect a good relationship between IOD and Citarum streamflow [7]. A new type of El Niño with warm (cool) waters in the central-equatorial Pacific Ocean and cool (warm) water in eastern and western Pacific is known as El Niño Modoki (La Niña Modoki) [15].

Table 1 Seasonal average and average ± Standard deviation values as per figure 2a climatology.

Season	Average daily streamflow (m^3/s)	Average daily + 1 SD streamflow (m^3/s)	Average daily – 1 SD streamflow (m^3/s)
DJF	99	167	31
MAM	102	162	41

Table 2 a) Extreme low and high river stream-flow (m^3/s) events together with the climate conditions during DJF season. mEl Niño and mLa Niña correspond to El Niño Modoki and La Niña Modoki respectively.* Years with no IOD and ENSO impacts and considered as normal years.

Extremely High Stream-flow Events	Average daily streamflows/ number of days
December-February	
1974-75 (La Niña)	239/11
1988-89(LaNiña,nIOD)	189/5
1988-89 (La Niña,nIOD)	239/17
1995-96 (La Niña)	211/5
1999-00 (La Niña)	200/5
2008-09 (La Niña)	265/6
1990-91 (mEl Niño)	221.5/6
2001-02 (mEl Niño)	301/15
2001-02 (mEl Niño)	518/10
2004-05 (mEl Niño)	404/8
1993-94*	249.5/11
Extremely Low Stream-flow Events	**Average daily streamflows/ number of days**
1977-78 (pIOD)	21/7
1982-83 (pIOD,El Niño)	14/5
1994-95 (pIOD,mEl Niño)	18/10
1997-98 (pIOD, El Niño)	23/7
1997-98 (pIOD, El Niño)	21/15
2006-07 (pIOD, El Niño)	26/10
2006-07 (pIOD, El Niño)	14/5
2007-08 (pIOD, La Niña)	34/6
2007-08 (pIOD, La Niña)	19/6
1981-82(LaNiña Transition)	25/14
2000-01(LaNiña Transition)	30/7
2000-01(LaNiña Transition)	11/15
1979-80*	10/64
2003-04*	4/54
2004-05 (mEl Niño)	28/7

As shown in the Table **2 a** and **b** the extreme events for both high and low stream-flow cases are calculated by five days or more continuous high or low stream-flow periods for each extreme case. We have excluded short events to focus on high frequency weather systems on the streamflow. It is found out that, in spite of the strong presence of intraseasonal oscillations, the extreme events of high and low stream-flows are actually related to IOD and ENSO during the study period [16]. In addition, some of the extreme stream-flow events are found to be related to the recently identified El Niño Modoki events [15].

Table 2 b) Same as table **2a** but for MAM season.

Extremely **High** Stream-flow Events	Average daily streamflows/ number of days
March-May	
1975(La Niña)	240/8
1988(La Niña)	189/8
1998(La Niña)	281/15
2005(La Niña,nIOD)	299/8
2005(La Niña,nIOD)	259/9
2005(La Niña,nIOD)	452/9
2007(La Niña)	284.5/11
1984(mLa Niña)	220/5
2001(mLa Niña)	272/8
2001(mLa Niña)	197/5
1979*	271/12
1993*	187.5/8
Extremely **Low** Stream-flow Events	Average daily streamflows/ number of days
1977(El Niño Transition)	39/6
1980(mEl Niño Transition)	27/5
1982(El Niño Transition)	29.5/10
1997(El Niño)	27/11
2002(mEl Niño Transition)	41/7
2004 (mEl Niño Transition)	47/5
2006(El Niño Transition)	23.5/7
2000(mLa Niña)	31/8
2000(mLa Niña)	22/12
2000(mLa Niña)	34/8
2000(mLa Niña)	38/16
2000(mLa Niña)	31/5
2008(mLa Niña)	29/13
1981*	41/6
1996(nIOD)	28/12
2005(nIOD,La Niña)	37/5

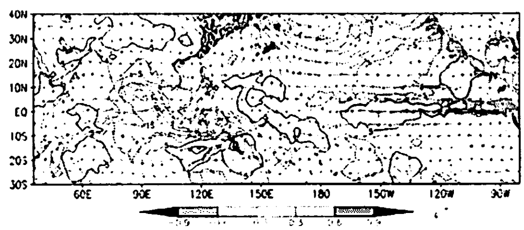
4 RESULTS AND DISCUSSION

(1) Climate impact on streamflow

Precipitation anomalies related to climate modes of the Indian and Pacific Oceans could influence the hydrology of the river basin [17]. Considering its large spatial extent, the stream flow of the river is directly influenced by large-scale climate forcing. In order to examine this aspect, classifications of the events are made in Table 2 according to the season and the phase of IOD and ENSO. The IOD generally evolves in late MAM, peaks in SON and decays thereafter [8]. On the other hand, though it evolves in MAM, ENSO peaks in DJF and generally continues until the spring of the following year depending upon the intensity of the occurrence [18].

(2)Climate Impact in DJF Season Streamflow

During this period of the year that coincides with the local monsoon season, the number of extreme events is higher and the duration of most of the events were longer as compared to that of the MAM season.The rainfall in this season is controlled by several modes of climate variation such as intraseasonal disturbances, monsoon, IOD and ENSO. Therefore, this season has nonlinear interactions among all those climate modes (Table 2). As shown in appendix the probability of a high stream to be associated with a La Niña is statistically significant compared to other climate modes though the value of probability is 0.54.



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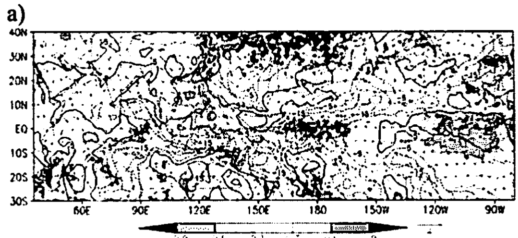

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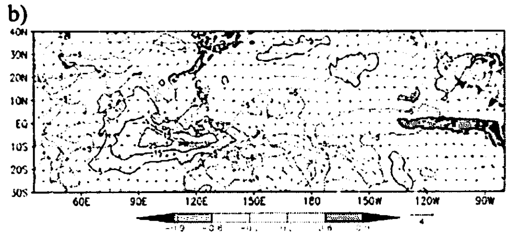

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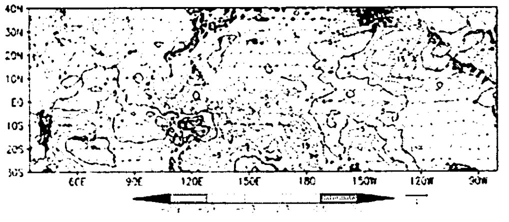


d)

Fig. 4 Composite anomalies of SST (shaded contour), wind (stream arrow) and OLR(line contour)during boreal winter season for a) all extreme high-stream-flow events, b) extreme high-stream-flow events associated with El Niño Modoki, c) all extreme low-stream-flow events, d) extreme low-stream-flow events associated with only La Niña events. Unit for SST is °C, for wind is m s^{-1}, and for OLR is w/m^2. Values above 95% confidence level from a two-tailed Student's *t* test are shown.

The distribution of events is quite diverse in the case of high-stream-flow cases when more than half (6 out of 11, **appendix**) of those events was associated with La Niña. The anomalies of SST, wind and OLR composited for all those events depict a La Niña condition when the eastern Pacific is colder and the seas surrounding the Maritime Continent are warmer than normal (**Fig. 4a**). The warm SST anomalies around Indonesia favor stronger low-level convergence, above normal rainfall and the high level of stream flows.

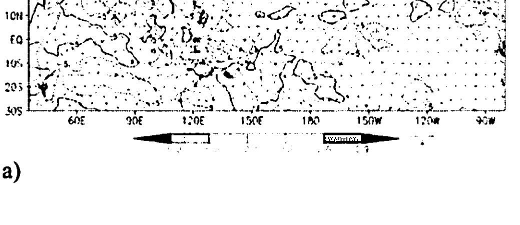
Some of the (that is 4 out of 11, **appendix**) high-stream-flow events were associated with the recently recognized El Niño Modoki mode [15), 19)]. The probability of the occurrence of high stream event during this mode is quite low,however it is higher than the likelihood of any one type of event happening in that season i.e., 0.33 associated with 3 types of modes. This mode with warm SST anomalies in the central Pacific aided warmer SST anomalies east of Java-Sumatra in the eastern Indian Ocean. While the descending branch of the anomalous Walker cell has caused overall deficit in rainfall over most of the Indonesia [20), 21)], it apparently aided a few pockets of local convections (**Fig. 4b**). The mechanism for such local intensification is not clear at this stage but it is seen that the warm SST anomalies east of Java introduced local meso-scale events in that region.

The extreme events of low-stream-flows depict a less dramatic picture with pIODs dominating the impact list (**Table 2**). More than half (i.e., 9 out of 15, **appendix**) of the events of the study period were associated with the pIODs. The probability of a pIOD event to be associated with extreme low streamflow is 0.60 much higher than the likelihood of any other occurrences (0.33 based on three types of modes in this season). The classification in Table 2 does not show an independent El Niño event that was uniquely associated with the low-stream-flow case though pIOD related El Niños accompanied 5 of them. The composite anomalies of SST and wind suggest a fall-over of pIOD condition with southeasterly anomalies off Java (**Fig. 4c**). The central Indian Ocean was warmer, driving moisture away from the region and suppressing the convection there.

This condition affected the development of seasonal rain bands and reduced the corresponding stream flows. Interestingly, we notice that 3 of the low-stream-flow events were associated with La Niña years in transition phases.. However, a closer look revealed that a couple of those events in 2007 were actually associated with a pIOD. The other 3 events were affected by the rapid turnaround of ENSO phases, when the ocean-atmosphere conditions in the Maritime Continent were not in La Niña-like state (**Fig. 4d**).

(3) Climate Impact in MAM Season Streamflow

The extreme high-stream-flow events in MAM were significantly (7 out of the total 12 events, **appendix**) associated with the La Niña years (**Table 2**). The probability of an extreme high streamflow event to be associated with La Nina is significantly higher than any other likelihood (0.58). The composite anomalies of SST, wind and OLR in Fig. 5a did not show a clear pattern of the La Niña impact as we saw in earlier season. Nevertheless, early development of warm SST anomalies and associated negative OLR anomalies are seen in Fig **5a**. Those are much clear in a composite of La Niña only events (**Fig. 5b**). From Fig. 5a, it is also noticed that the western and eastern Indian Ocean was warm during some of the extreme high-stream-flow events as the basin was giving rise to nIOD events later in the season.



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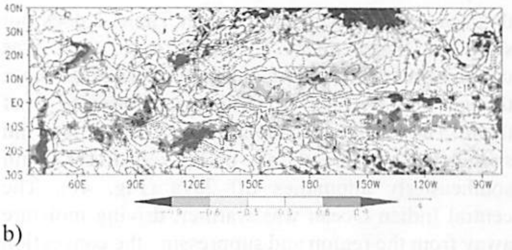

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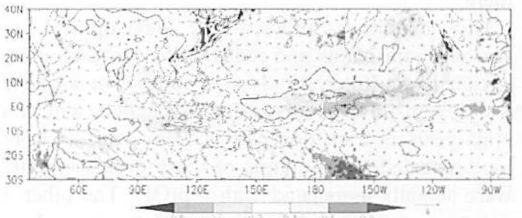

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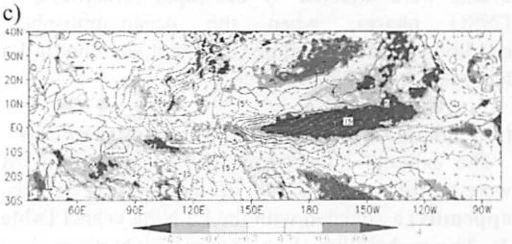

d)

Fig. 5 Same as fig.4 but MAM season for a) all extreme high-stream-flow events, b) extreme high-stream-flow during only La Niña events c) all extreme low-stream-flow events and d) extreme low-stream-flow events associated with La Niña Modoki. Units and values as in Fig.4.

The low-stream-flow events in this season are affected by several phenomena but majority (about one-third, **appendix**) were associated with ENSO transition conditions (sometimes appearing like ENSO modoki with opposite SST anomalies in eastern and western Pacific from that of the central Pacific). Together with La Niña modoki, these transition phases account for a very high probability ~0.8 of getting extreme low-stream flows during the season. The associated anomalies of SST, wind and OLR clearly depict La Niña Modoki in composites of all low-stream-flow events (**Fig. 5c**). The anomalies were understandably stronger and convincing in the composite of low-stream-flow events that were uniquely associated with La Niña Modokis (**Fig. 5d**). The shift of cold anomalies to the central Pacific in La Niña Modoki events apparently creates colder conditions on Java-Sumatra coast. This could suppress the convection locally to reduce the stream-flow. The cause of the cold anomalies off Java-Sumatra is not immediately clear from our analyses. But it is possible that the transition to La Niña Modoki phase in the Pacific might have reduced the volume of heat transport.

5. CONCLUSIONS

In this study we analyzed the extreme streamflow characteristics with the climate variability e.g. IOD, ENSO and ENSO Modoki. We considered peak rainy seasons (December-May) streamflow at Nanjung gauge stations of the Citarum River for the study. Apparantly the result shows the stronger influences of pIOD to the extreme low streamflow events during DJF season. On the other hand above 95% confidence level from a two-tailed Student's *t* test composite index of La Niña Modoki events of the MAM season shows a convincing impact to the extreme low streamflow events during this season. The dominant influences of La Niña Modokis are recognized in case of the low-stream-flow events as depicted in the composite anomalies of that season. In DJF and MAM, a majority of high-stream-flow events were associated with the La Niña developments. The extremely high streamflow event for both the season of DJF and MAM, La Nina plays a stronger role with 0.54 and 0.58 likelihood much higher than base level of 0.33 with 3 type's occurrences in those seasons. However, in DJF few recently recognised El Nino Modoki events occurred uncharacteristically which needs further case by case investigation.

According to Luo *et al* [22] IOD can be predicted several months prior of the event therefore could be helpful for the river basin management. There are several other processes that need further investigation about the stream-flow variations. For example a few of the low-stream-flow events were uncharacteristically associated with the La Niña condition in the Pacific. On the other hand, several high-stream-flow events were associated with El Niño Modoki in DJF when the overall rainfall over Java and eastern Indian Ocean was suppressed by the descending branch of anomalous Walker circulation.

Since most of the climate variations in the Indo-Pacific sector are predictable on seasonal to interannual scales, the regional impacts shown here will help to extend those predictions to local level, which will help the regional communities dependent on the river discharges. Besides its social impact, this study will attract the attention of the climate and hydrology research groups to investigate those climate links further. This study clearly showed the direct impact of the Indian Ocean Dipole and the El Niño/La Niña on the regional river discharges. This scientific contribution shows a dominant influence of climate variation as compared to any other factors responsible for river discharges even on shorter time scales.

APPENDIX

Number of extreme streamflow events for different seasons associated with modes of climate variations in Indian and Pacific Oceans. Values with bold fonts are statistically significance and suggest the maximum likelihood of that type of event during the concerned season.

Occurrences	Events	Total	Probability	Probability of any type of occurrences	Types of occurrences
High Stream Flow December-February					
La Nina and nIOD+La Nina	6	11	**0.54**		
mEl Nino	4	11	**0.36**	0.33	3 types
Others	1	11	0.1		
Low Stream Flow December-February					
pIOD, pIOD+El Nino, pIOD+La Nina	9	15	**0.60**		
Others	3	15	0.20	0.33	3 types
Transition	3	15	0.20		
High Stream Flow March-May					
La Nina and nIOD+La Nina	7	12	**0.58**		
mLa Nina	3	12	0.25	0.33	3 types
Others	2	12	0.17		
Low Stream Flow March-May					
El Nino, El Nino and mEl Nino transitions	7	16	**0.43**		
mLa Nina	6	16	**0.37**	0.33	3 types
Others	3	16	0.18		

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