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RESEARCH ARTICLE

Changes in runoff and eco-flow in the Dongjiang River of the Pearl River Basin, China

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Abstract The Dongjiang River, one of the tributaries of the Pearl River, serves as the critical water source for Guangdong Province and the District of Hong Kong in China. In this study, the change trend and change points of flow at three main gaging stations in the Dongjiang River were analyzed using the nonparametric Mann-Kendall test and Pettitt-Mann-Whitney change-point statistics. Flow regime changes in the Dongjiang River were quantified by using both the Indicators of Hydrologic Alteration (IHA) parameters and eco-statistics, such as ecosurplus and ecodeficit. It was found that the change trend for annual median flow in the Dongjiang River increased over the past 60 years, with the major change occurring sometime between 1970 and 1974. IHA analyses showed that the magnitude of monthly flow decreased during the flood period, but increased greatly during the dry period. The median date of the one-day minimum flow moved ahead, and the duration of low pulse for the Dongjiang River was reduced significantly because of reservoir construction and operations. The IHA-based Dundee Hydrological Regime Alteration Method analysis indicated that all three stations have experienced a moderate risk of impact since 1974. The eco-statistical analyses showed that the majority of the flows appeared to be ecosurplus at all three locations after 1974, while flows with less than 30%, or higher exceedance probability, had ecodeficit in the summer flood period due to heavy reservoir operations.

Keywords hydrologic alteration, change point analysis, runoff, eco-flow

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1 Introduction

Hydrological systems have become more and more complicated as a result of human activities, such as the construction of reservoirs. In addition, land use and climate changes, including atmospheric circulation, precipitation, and air temperature, result in hydrologic alterations in terms of the magnitude, frequency, duration, and timing of flow regime. River discharge and flow regime changes are well recognized by ecologists as the primary drivers for a number of fundamental ecological processes in river ecosystems (Poff and Zimmerman, 2010). More and more researchers worldwide have recently focused on the hydrologic alteration of watersheds and its impacts to the ecosystem (Richter et al., 1996; Magilligan and Nislow, 2005; Mathews and Richter, 2007; Piao et al., 2010; Poff and Zimmerman, 2010; Sabater and Tockner, 2010; Suen, 2010; Kim et al., 2011; Zhang et al., 2011; Fernández et al., 2012; Gao et al., 2012; Lian et al., 2012; Zhao et al., 2012). Accordingly, researchers have developed and applied a number of statistical tools and methods to characterize the various aspects of flow regimes to assess and quantify the ecological effects from hydrologic alterations.

The Indicators of Hydrologic Alteration (IHA), developed by the Nature Conservancy in the United States (Richter et al., 1996), is one of the most widely used suites of hydrologic metrics, which includes the range of variability (RVA) method to evaluate changes of the river flow regime (Richter et al., 1998). In recent years, a large and rapidly growing body of literature has been published on hydrologic alteration and its impact on ecosystems, focusing mainly on the impact of two aspects: climate change and reservoir operation. For example, Magilligan and Nislow (2005) applied the IHA method to assess hydrologic changes associated with dams in the U.S., and found that they had significant impacts on the entire range of hydrologic characteristics measured by IHA. Suen (2010) also used the IHA method to assess the potential streamflow alterations caused by changing climate conditions and how these changes may potentially affect the freshwater ecosystems in Taiwan. Since Flow Duration Curves (FDCs), which can condense a wealth of hydrological information into a single graphic image, are often used to summarize the impacts of potential climate change scenarios on water resource systems (Vogel and Fennessey, 1995), Gao et al. (2009) developed a few statistics to capture the key components of ecologically relevant flow variations using an eco-flow metrics (ecosurplus and ecodeficit) calculated from FDCs. By comparing the eco-flow metrics with IHA metrics, Gao et al. (2012) suggested that a combination of the two metric groups provided a sufficient measure of changes in the flow regime.

China is the world's most populous country and is potentially a major emitter of greenhouse gases. Much research has been focused on China's influence on climate change (Piao et al., 2010). In addition, the increase in human activities due to rapid development in recent years, including the construction of a number of large dams and reservoirs, has the potential to affect the environment. Changes in river discharges and flow regimes were examined in many regions of China (Chen et al., 2007; Cong et al., 2009; Chen et al., 2010; Gao et al., 2012; Liu et al., 2012). The Dongjiang River basin serves as a critical water resource to the Guangdong Province and the District of Hong Kong in China. However, due to rapid economic development and urbanization, the quantity and quality of available water resources in the Dongjiang River basin have become serious issues. Many studies have been conducted to investigate the impacts of climate change and human activities on water resources and the ecosystem on the Dongjiang River basin. Jiang et al. (2007) investigated the response strategies for water supply and flood control due to climate change by comparing the hydrological impacts of climate change simulated from six models for the Dongjiang River basin. Analyses by Wang et al. (2008) found little change in annual extreme precipitation in terms of various indices, but found some significant changes in precipitation processes on a monthly basis. A study by Liu et al. (2010) showed that climate variability and human activity each accounted for about 50% of the runoff change in the Dongjiang River basin during the low-flow period from 1956 to 2000. In the same manner, Chen et al. (2010) analyzed the hydrologic alteration from 1952 to 2002 in the middle and upper Dongjiang basin. However, many studies (Peng et al., 2008; Chen et al., 2013; Zhang et al., 2013a) have shown an increase in temperature and variability of precipitation in the river basin as a result of climate change in recent years. During the same time, human activities have intensified due to regional economic development which has resulted in higher water demands (Zhang et al., 2013b). Literature review shows there is a lack of analyses on eco-flow changes and their possible impacts on the river ecosystem in this region.

This paper aims to: (i) analyze the trends and variability of the flow regimes in the Dongjiang River basin using the long-term flow data; and (ii) examine and quantify flow regime changes in the river basin by using the recently introduced eco-flow metrics (ecosurplus and ecodeficit) and IHA parameters.

2 Materials and methods

2.1 Study area and data

The Dongjiang River is one of largest tributaries of the Pearl River, and is located in the Guangdong and Jiangxi provinces in southern China. The basin has a sub-tropical monsoon climate strongly influenced by storms from the South China Sea and the Western Pacific, and is impacted by southwest monsoons and typhoons. The annual average temperature is 20.4°C, and the annual average precipitation ranges from 1,500 to 2,400 mm. The variation coefficient for the spatial rainfall distribution is about 0.22, indicating an uneven distribution of precipitation. There is typically more rainfall in the lower and middle sections of the basin than in the upper basin, and more in the southwest basin than in the northeast, with precipitation decreasing from the south to the north. The annual average temperature of the basin is between 20°C and 22°C, and the annual average evaporation is between 1,000–1,400 mm. Spatially, the evaporation in the southwest is stronger than in the northeast. The precipitation in the basin has great seasonal variations; almost 80% of the yearly rainfall occurred from April to September. Presently, Dongjiang River provides the essential water supply to several major cities, such as Guangzhou, Shenzhen, Dongguan in the Pearl River Delta region, and also to the District of Hong Kong.

The construction of three major reservoirs, i.e., the Fengshuba, Xinfengjiang, and Baipengzhu on the Dongjiang River, were completed in 1974, 1962, and 1985, respectively, in the upper, middle, and lower reaches of the river (Fig. 1 and Table 1). Chen et al. (2010) studied the hydrologic alteration of the Fengshuba and Xinfengjiang reservoirs based on the 1951–2002 data series by using the RVA method. In this study, not only were the longer term flow data employed (from 1951 to 2010), but more importantly, additional statistical metrics were used to evaluate and quantify the hydrological changes in the Dongjiang River from more aspects.

2.2 Analysis methods

2.2.1 Indicator of Hydrologic alteration (IHA) and DHRAM

The IHA statistical package, developed by Richter et al.

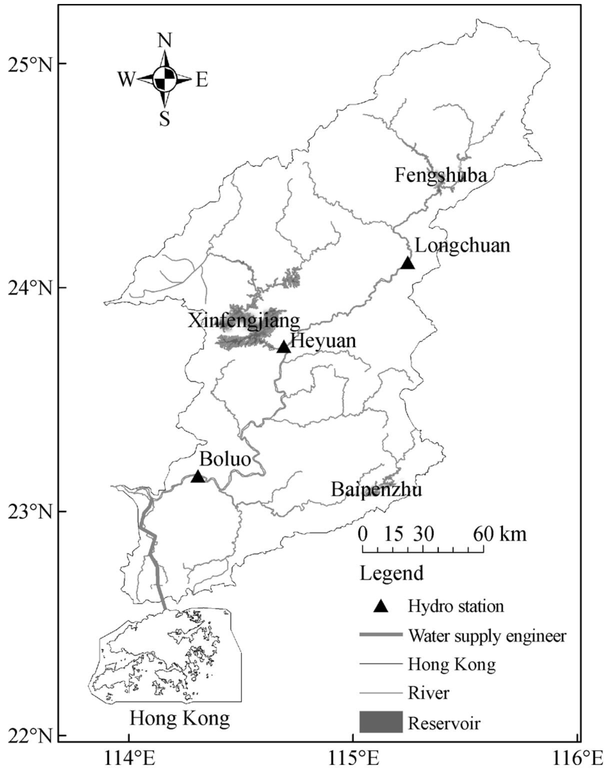

Fig. 1 Study area, location of the hydrological station, and three major reservoirs.

(1996, 1998) and supported by The Nature Conservancy (TNC), was used to calculate the hydrologic alteration on the Dongjiang River. IHA computes 33 parameters from historic flow or stage records, including five characteristics of flow regimes, which are called magnitude of monthly water conditions, magnitude and duration of annual extreme conditions, timing of annual extreme conditions, frequency and duration of high and low pluses, and rate and frequency of condition changes. The Range of Variability Approach (RVA) method is used to quantify the degree of alteration for each hydrologic parameter in IHA. This method divides the full range of pre-modification data into three different categories: low, middle, and high (Richter et al., 1998; Lian et al., 2012). The Dongjiang River basin is a large basin. No zero-flow day was ever observed at three gaging stations during the study period; therefore, the "number of zero flow days" was not considered in this study, and due to the lack of base flow analysis, the "base flow index" was also not considered.

Another method, the Dundee Hydrological Regime Alteration Method (DHRAM) developed by Black et al. (2005), was used in this study to classify the risk of impact to instream ecology. DHRAM yields a score (from 0 to 30) based on the overall percentage of change in the IHA parameters. A final DHRAM classification of impact severity on a 1–5 class scale (Table 2) is obtained to assess the severity and extent of human alteration to hydrologic regimes (Black et al., 2005; Gao et al., 2009).

2.2.2 Eco-flow statistics

The concept of eco-flow statistics, proposed by Vogel et al. (2007) and used by Gao et al. (2009), was selected to represent another generalized index of hydrologic alteration of streamflow time series. Gao et al. (2009) divided the year into three seasons and used the median flow duration curve as a comparative criterion to assess the hydrologic alteration. Gao et al. (2012) suggested the 25th and 75th

Table 1 Geographical properties of reservoirs and the hydrologic station on the Dongjiang River

Reservoir			Downstream hydrologic station				
Name	Total capacity/(10^8 m^3)	Construction/year	Name	Location		Drainage area/km^2	Series length
				Longitude	Latitude		
Fengshuba	138.96	1970–1974	Longchuan	115°15'E	24°07'N	7,699	1952–2010
Xinfengjiang	19.32	1958–1962	Heyuan	114°42'E	23°44'N	15,750	1951–2010
Baipengzhu	12.2	1977–1985	Boluo	114°18'E	23°08'N	25,325	1953–2010

Table 2 Definition of DHRAM classes

Class	Score range	Description
1	0	Unimpacted condition
2	1–4	Low risk of impact
3	5–10	Moderate risk of impact
4	11–20	High risk of impact
5*	21–30	Severely impacted condition

Questions
1. The classification is dropped (down the table) by one if anthropogenic sub-daily flow fluctuations exceed 25% of the 95% exceedance flow, and/or
2. provisionally dropped by one class if flow cessation occurs as a result of the anthropogenic process(es).
* Class 5 is the lowest classification that can be allocated.

percentile FDCs could also be used for comparison. Eco-statistics is a good method for understanding the flow change at different flow frequencies. The eco-statistics method allows for the use of the period flow record and for median flows. It was suggested that median flows be used to avoid the impact from extreme events. Therefore, this study used median flow duration curves to evaluate the hydrologic alteration between the pre- and post-change series, as shown in Fig. 2. Based on the hydroclimatic conditions in the Dongjiang River basin, four seasons or time periods were considered in a year, i.e., spring (March–May), summer (June–August), fall (September–November), and winter (December–February). The ecosurplus and ecodeficit indices were computed for each season and also for the entire year.

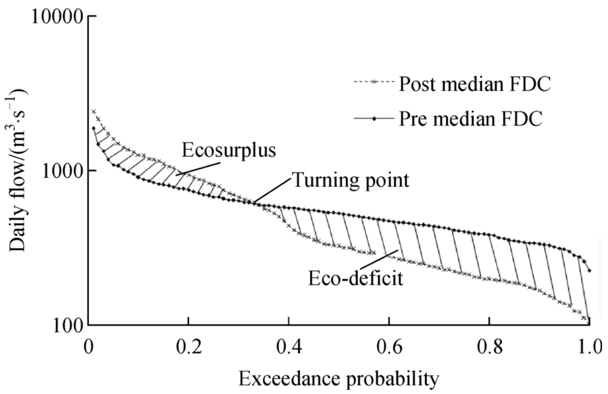

Fig. 2 Definition of ecosurplus and eco-deficit in the flow duration curve.

2.2.3 Change-point analysis method

The rank-based Mann-Kendall test (Mann, 1945; Kendall, 1975; Hirsch et al., 1982) and the nonparametric Pettitt-Mann-Whitney test (Fealy and Sweeney, 2005) were applied to efficiently identify the change points of the runoff series in this paper.

3 Results and discussion

3.1 Runoff trends and their variations

Figure 3 showed the trend and change point analyses of the annual median flow data at Longchuan, Heyuan, and Boluo stations. Each figure shows the Mann-Kendall and Pettitt-Mann-Whitney test results for each station. The Mann-Kendall test analyses showed a slight increasing trend of annual flow at three gaging stations. Based on these test results, the possible change points were examined for the annual flow, with long-term records starting during or before 1953. The change point for the annual flow in the Dongjiang River was identified as the time period from 1970 to 1974, which was statistically significant at the Longchuan and Heyuan stations, but not at the Boluo station. Coincidently, this change was due to a combination of climate change and rapid economic development during that time in the Dongjiang basin (Huang et al., 2006) and the construction of Fengshuba and Xinfengjiang reservoirs around the same period. In addition, the Boluo station (located in the lower reach of the Dongjiang River, far from Fengshuba and Xinfenjiang reservoirs) and the relatively small, total capacity of the nearest reservoir (Baipengzhu) are capable of receiving the natural confluence from other tributaries and the district area to reduce the impact of reservoir operation.

Studies by other researchers (Wang et al., 2008; Liu et al., 2010; He et al., 2013) showed that the annual runoff changes in the Dongjiang River were mainly affected by climate change and human activities. A study by He et al. (2013) showed that temperature increased significantly and evaporation and sunlight decreased sharply, while precipitation showed a nonsignificant increase in the Dongjiang basin. Climate change increases the frequency of flooding (Meehl et al., 2000). On the other hand, land uses in the Dongjiang basin have experienced a significant change since the 1980s, with a prominent increase in urban areas, a moderate increase in farmlands, and a significant decrease in forest areas (He et al., 2013). Both expansion of urban area and deforestation in the basin provided contributing factors that affected hydrological processes and subsequently increased runoff. The change in runoff yield became more instantaneous and more sensitive to precipitation, along with the land cover conversion from forest to urban areas.

3.2 Hydrologic alteration of reservoir

It has been shown that the runoff changed statistically after 1974 in a positive trend as a result of climate change and human activities. It is difficult to separate the impact of reservoir development from climate change because the construction of reservoirs and climate change occurred around the same period in the Dongjiang River basin. However, it is apparent that the Fengshuba reservoir construction from 1970 to 1974 had a major impact on its downstream flows. The long-term records were divided into the pre-change period of 1951–1969 and the post-change period of 1975–2010 for the IHA and eco-statistical analyses in this study. The DHRAM analysis was performed to assess the degree of hydrologic alteration in the Dongjiang River.

The 31 parameters selected to analyze the hydrologic alteration on the Dongjiang River include the monthly average flow; 1-, 3-, 7-, 30-, and 90-day minimum and maximum average flows; the date when minimum and

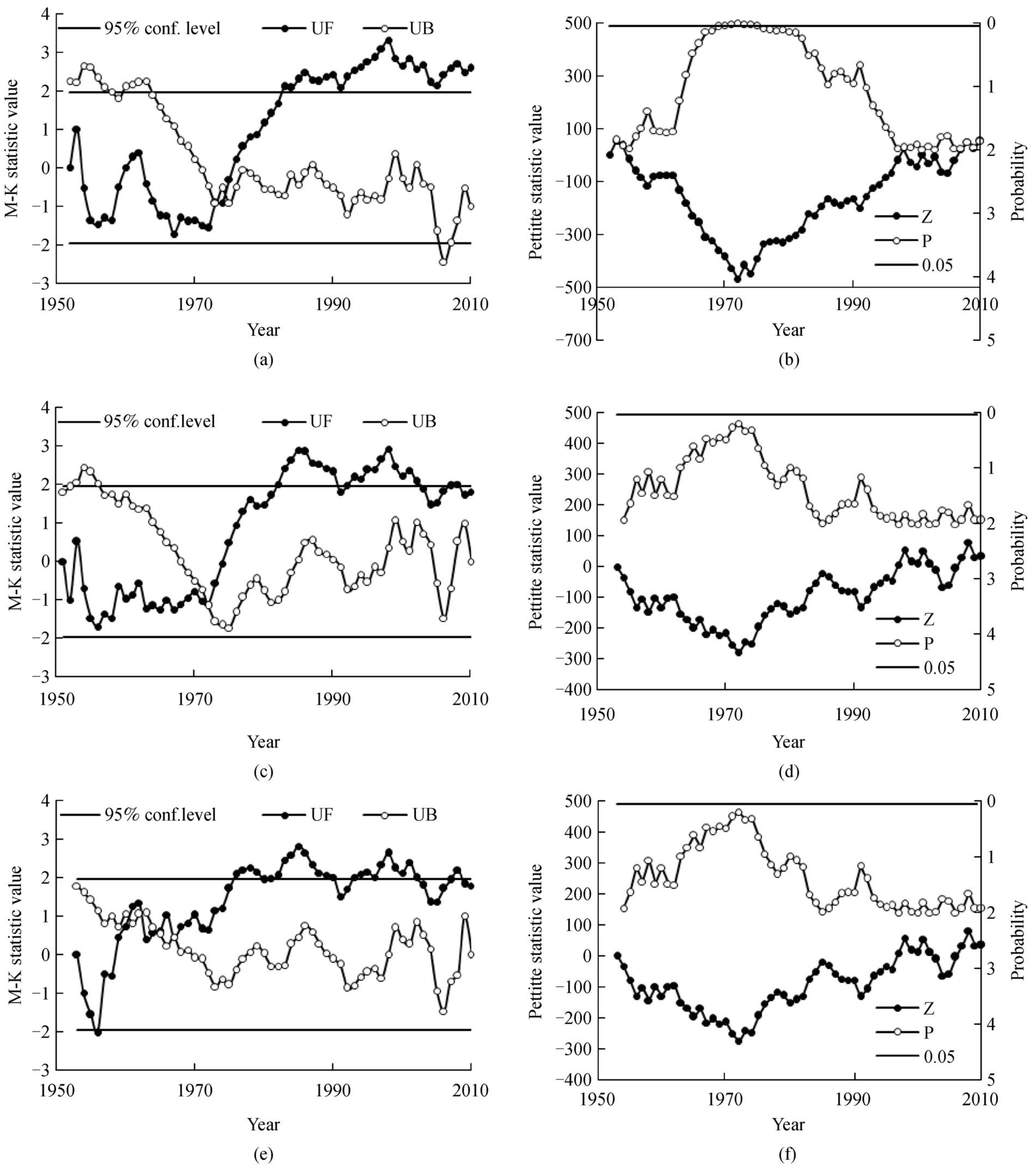

Fig. 3 The results of the runoff trends and change points analysis ((a) and (b) for Longchuan, (c) and (d) for Heyuan, (e) and (f) for Boluo).

maximum stage and flow occurred; low and high pulses and their durations; and number of reversals. The results for IHA analyses are listed in Table 3 for the Longchuan, Heyuan, and Boluo stations. The representative columns for each station include the median of each IHA parameter for the pre- and post-periods, the absolute and relative change of the medians, and the RVA boundary values. The hydrologic alteration quantifies from RVA and the classification of changes are shown in the high (H), medium (M), and low (L) categories. Table 3 also shows that the monthly river flow has a high alteration after 1974, especially in the dry periods. The magnitude of monthly flow decreased during the flood period, but increased greatly during the dry period due to reservoir operations at Longchuan and Heyuan stations. This is because the reservoirs usually operate to store flow in the flood period but release flow in the dry period. Table 3 also shows that the degree of change in the dry period ranged from medium (M) to high (H) for most months at all three stations. Specifically at the Boluo station, the medians of all monthly flows increased slightly (Table 3), indicating that the impact of upstream reservoirs diminished with the distance downstream. In addition, reservoir operations have caused a decrease in maximum flow and an increase in minimum flow. Due to changes in monthly flows and annual extreme conditions, there are potential influences on the reduction of biodiversity, decrease of aquatic macrophyte, and increased fine sediment deposition (Richards and Bacon, 1994).

The occurrence time for the one-day annual minimum and maximum water conditions in Julian date is crucial for the seasonal feature of the hydrologic conditions. The median date of the one-day minimum flow moved ahead by about 35, 17.5, and 10.5 days at Longchuan, Heyan, and Boluo stations, in post-modification conditions, respectively (Table 3). The change of occurrence time for the annual minimum and maximum water conditions can disrupt spawning of fish with pelagic eggs, because spawning activity for many fish is triggered by both rising water and rising temperatures in the spring (Lian et al., 2012). The *Tenualosa reevesii* (Reeves shad), a famous anadromous fish in China, were able to migrate upstream to the Xinfengjiang for spawning and breeding in the 1960s, but since the 1970s, conditions have made this migration impossible (Lu, 1990). Compared with the data collected in the 1980s, the proportion of sedentary and omnivore species increased, while migratory and carnivore species declined (Liu et al., 2011).

The fourth IHA parameter group is hydrologic pulse and duration. The duration of low pulse for the Dongjiang River was reduced significantly because of reservoir operations for water supply during the dry period. Another high alteration group is rate and frequency of change in conditions, especially at Longchuan and Heyuan stations. The IHA values of the fall rate and number of reversals were close to -100%, with a significant increase in the medians for both indices, indicating a more frequent change in the flow regime on the Dongjiang River after 1974. Rapid changes, including flow reversals, can disrupt the biological life cycle resulting in the disappearance of native species and an invasion of alien species. As a result of the Fu et al. (2011) two year investigation on the riparian zone of the Dongjiang River, 51 species of alien invasive plants were found, including 17 families and 38 genera, such as ageratum conyzoides and chenopodium ambrosioides. Another potential effect of flow reversals is a decreased variability in the catch of young fish.

To better summarize the results from IHA analyses, the DHRAM classification was used to categorize the risk or impact of overall hydrologic alterations at three gaging locations (Table 4). The total DHRAM scores at Longchuan, Heyuan, and Boluo were 7, 10, and 8, respectively, indicating a moderate impact on the overall hydrologic alterations on the Dongjiang River. The Heyuan station, affected by the Xinfenjiang reservoir which is controlled by the largest dam in Guangdong Province, with a total storage capacity of $138.96\times10^8\,m^3$ of water, had the greatest impact among all three stations. The Boluo station had the least impact with a contribution of flows from other natural streams downstream and from the upstream reservoirs.

3.3 Changes in the eco-flow

The median flow duration curves were computed for four seasons and also for the annual flow for the pre- and post-change periods. Comparisons of the seasonal median flow duration curves for these change periods are shown in Fig. 4 for the Longchuan station. Vogel et al. (2007) defined the change as ecosurplus if the post-flow was higher than the pre-flow for the same frequency, or, as ecodeficit when the order was reversed. In this study, the turning point was defined as the point at which flow regimes transition from ecosurplus to ecodeficit or vice versa, as shown in Fig. 2. It can be seen from Fig. 4 that based on the eco-statistical analyses,most of the annual and seasonal eco-flow changes had a surplus with little or no deficit, while there was a deficit in the summer flood period at the Longchuan station.

Table 5 lists the ecosurplus, ecodeficit, the exceedance frequency, and its corresponding median flow of the turning point for all four seasons and for a year. As shown in Fig. 4 and Table 5, obvious eco-deficit conditions only occurred during the summer season at three gaging locations; a majority of the flows appeared to be ecosurplus at all three locations after 1974. The turning points showed that flows with less than 30% or higher exceedance probability, had ecodeficit in the summer, but flows that had an ecodeficit also had a smaller exceedance probability for other seasons at three locations. It can also be seen that there was more ecosurplus than ecodeficit, which may be primarily due to the reservoir operations for reducing peak flow in the summer and storing flow in the dry period. A comparison of the annual and seasonal FDCs also showed that for the same flow, particularly low flows, the exceedance probability had increased in the post period at all three stations, reflecting an increase of duration for low flows.

Studies by Magilligan and Nislow (2005), Poff and Zimmerman (2010), and Suen (2010) showed that hydrologic alteration can significantly impact ecosystems. This is particularly true for high alteration in the summer, the season when fish and plants experience their most rapid period of growth, thus affecting their biological life cycle. Alternatively, the magnitude and duration of low flow increases in the Dongjiang River could possibly maintain

Table 3 IHA analyses of the flow regime at Longchuan, Heyuan, and Boluo stations

Indicators	Longchuan				Heyuan				Boluo			
	Medians		Hydrologic alteration		Medians		Hydrologic alteration		Medians		Hydrologic alteration	
	Pre	Post	Value/%	Category	Pre	Post	Value/%	Category	Pre	Post	Value/%	Category
Magnitude of monthly river flow/($m^3 \cdot s^{-1}$)												
January	57.25	117	−75	H	170	345.5	−77.38	H	232	400.5	−79.76	H
February	67.25	115.8	−91.67	H	163	351.3	−32.14	L	231	367.8	−66.27	M
March	70.2	139	−41.67	M	205	368	−69.84	H	249	427	−73.02	H
April	116.8	242	−50	M	320.5	480.3	−47.22	M	402	591	−59.52	M
May	186	294.5	−25	L	524	551.5	28.17	L	581	776	21.43	L
June	380.3	313.3	91.67	H	841.5	684.5	73.41	H	1041	1125	21.43	L
July	152.5	250.5	−16.67	L	398	628.5	−39.68	M	724	912.5	34.92	M
August	135	233	−33.33	M	393	586	−54.76	M	640	926	−52.78	M
September	105.3	177.5	−75	H	339.5	488	−69.84	H	586	772.5	−79.76	H
October	82.3	140	−58.33	M	264	351.5	−47.22	M	396	542	−59.52	M
November	63.75	125.3	−75	H	207	328.8	−47.22	M	343	434.5	−25.79	L
December	51.85	111.5	−66.67	M	190	324.5	−54.76	M	256	407	−46.03	M
Magnitude and duration of annual extreme conditions/($m^3 \cdot s^{-1}$)												
1-day minimum	31.05	28.35	−25	L	78.2	149	−62.3	M	117	226.5	−82.29	H
3-day minimum	32.45	35.37	−33.33	M	87.8	169.7	−54.76	M	128	243.3	−79.76	H
7-day minimum	33.33	44.74	−58.33	M	91.29	192.5	−39.68	M	128	264.1	−52.78	M
30-day minimum	40.32	72.3	−66.67	M	128.8	239.5	−62.3	M	174.5	310.2	−79.76	H
90-day minimum	67.41	114.7	−33.33	M	187.7	310.1	−47.22	M	240.5	384	−79.76	H
1-day maximum	2210	1075	−50	M	3480	1745	−69.84	H	5530	4440	21.43	L
3-day maximum	1492	817.3	−66.67	M	3147	1583	−77.38	H	4657	3960	28.17	L
7-day maximum	973.4	633.3	−8.33	L	2256	1228	−47.22	M	3747	3009	61.9	M
30-day maximum	659.4	461.8	16.67	L	1450	864.3	−24.6	L	2360	1789	21.43	L
90-day maximum	418.6	369	16.67	L	876.5	755.2	20.63	L	1432	1340	28.17	L
Time of annual extreme conditions/days												
Date of minimum	72.5	37.5	0	L	49	31.5	−47.22	M	41	30.5	−40.97	M
Date of maximum	159.5	157.5	−41.67	M	168	164.5	−32.14	L	176	179.5	−12.3	L
Frequency and duration of high and low pulses												
Low pulse count	6	6.5	−42.86	M	5	3	−64.81	M	5	1	−63.27	M
Low pulse duration	8	2	−100	H	5.5	2	−47.22	M	8.25	3	−68.52	H
High pulse count	12.5	15.5	−22.22	L	12	15	−38.43	M	9	9	−33.89	M
High pulse duration	3	3	−50	M	3	3	−36.67	M	5	4.5	6.25	L
Rate and frequency of change in conditions												
Rise rate	21.35	20.93	141.7	H	24.5	38	80.95	H	44	31.5	34.92	M
Fall rate	−8.35	−19.25	−100	H	−20	−40.5	−100	H	−23.5	−41	−73.02	H
Number of reversals	85	177.5	−100	H	107	182	−100	H	81	134	−100	H

the flow conditions essential for sustaining the ecosystems during the dry period. Maintaining minimum flow in the Dongjiang River is crucial when water is being withdrawn during the low flow periods to ensure water demand is met for industrial and domestic usages, which ultimately impairs the water balance for biological demand. It is expected that the research results from this study will provide information for better water resource management

Table 4 The results of DHRAM at three stations on the Dongjiang River

Station	Original data series				
	IHA score	Mean change/%		Impact points	
	Group	Medians	CV	Medians	CV
Longchuan	1	78.74	33.57	3	1
	2	37.48	64.96	0	0
	3	10.11	26.80	1	0
	4	26.83	51.69	0	1
	5	80.43	41.52	1	0
	Total points				7
	Final classification				3
Heyuan	1	57.12	29.75	2	1
	2	64.51	51.15	1	0
	3	5.74	68.57	0	3
	4	32.16	60.75	0	1
	5	75.90	64.32	1	1
	Total points				10
	Final classification				3
Boluo	1	43.09	40.87	1	1
	2	51.24	29.00	1	0
	3	3.83	15.20	0	0
	4	38.41	159.31	1	3
	5	56.10	42.07	1	0
	Total points				8
	Final classification				3

to meet not only both industrial and residential water supply needs, but also provide ecosystem sustainability throughout the region.

4 Conclusions

As one of the major water supply resources for the Pearl River Delta and the District of Hong Kong in China, three large water reservoirs were built for flood control and more importantly, to maintain water supply during the dry periods. Numerous studies have been conducted on water resource management of the Dongjiang River to ensure adequate water supply over the years. This study focused on the change of hydrological regimes and their potential ecological impact in the system. Major findings from this study include:

(i) The trend analysis showed that there was an increasing trend in the annual median flow in the Dongjiang River basin from 1951 to 2010. The period of 1970–1974 was identified as the flow change period when both the construction of reservoirs on the river and climate change occurred, coincidently.

(ii) Results from the IHA analyses showed that since 1974, the monthly river flow has had a high alteration in the upper Dongjiang River, especially in the dry periods. It also showed that the median for the date of the minimum moved ahead greatly, and that the rate and frequency of change belong to high alteration, especially for the greater increase in the number of reversals. DHRAM analyses indicated a moderate risk of impact on overall hydrologic alterations on the Dongjiang River.

(iii) Analyses of eco-flow change in this study showed that most annual and seasonal changes are ecosurplus with little ecodeficit, except in the summer when the values of ecodeficit are greater than, or almost equal to, those of ecosurplus, due to reservoir operation in the summer flood period. In general, ecodeficit occurs in the high flow period and ecosurplus in the low flow period. In addition, the magnitude and duration of flow increase during the low flow period.

The hydrologic alteration due to human activities and climate change should manifest in significant ecological adjustment on the Dongjiang River. The major potential ecosystem influences include changes in biological life cycles, especially for fish with pelagic eggs, disappearance

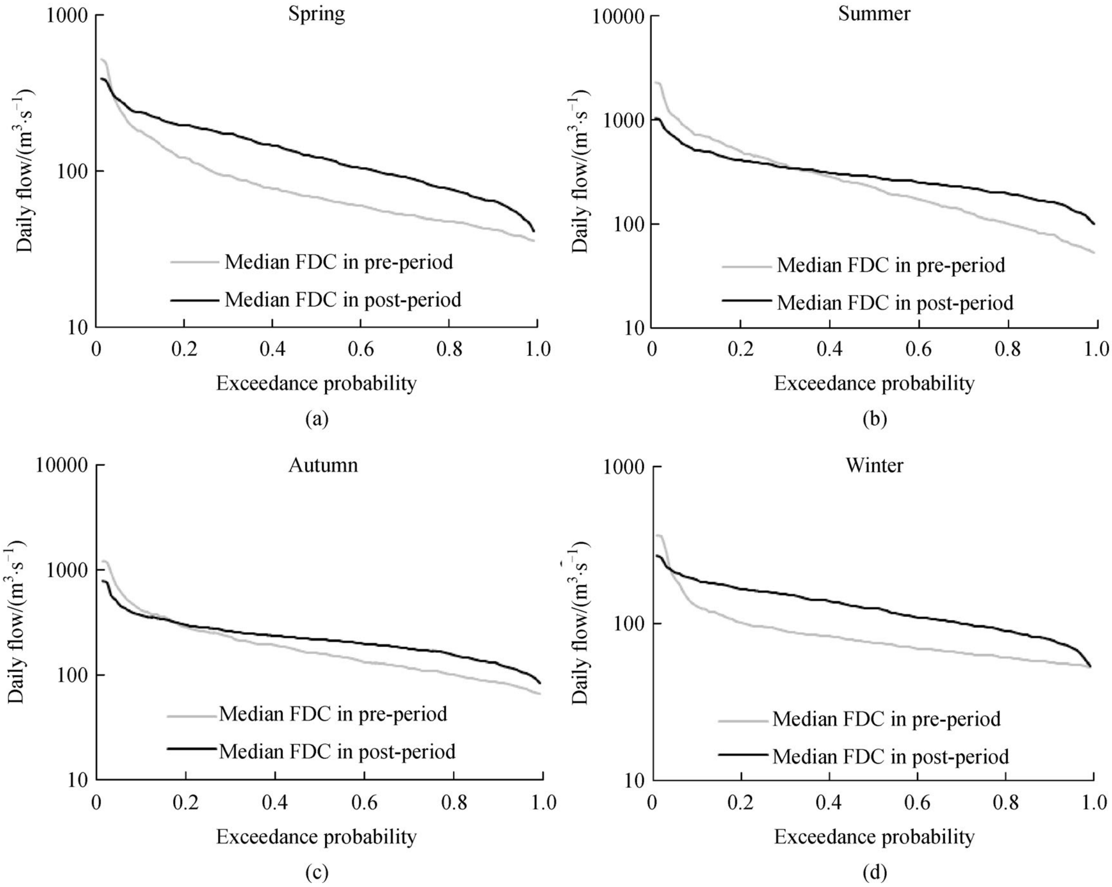

Fig. 4 The seasonal FDCs between pre- and post-data series at Longchuan ((a) for Spring, (b) for Summer, (c) for Autumn, (d) for Winter).

Table 5 The results of eco-flow analyses on Dongjiang River

Station	Type	FDC Area		Area different		Eco different		Turning point	
		Pre	Post	Absolute	Re/%	Ecosurplus	Eco-deficit	Probability	Flow/($m^3 \cdot s^{-1}$)
Longchuan	Spring	91.41	137.13	45.72	50.01	0.52	0.02	0.05	293
	Summer	338.13	317.22	–20.92	–6.19	0.14	0.20	0.32	343
	Autumn	213.54	232.16	18.62	8.72	0.18	0.09	0.18	305
	Winter	87.98	127.32	39.34	44.72	0.47	0.02	0.05	194
	Annual	169.66	197.25	27.59	16.26	0.25	0.09	0.14	312
Heyuan	Spring	229.19	371.44	142.25	62.07	0.62	0.00	0.04	586
	Summer	718.68	643.16	–75.52	–10.51	0.08	0.19	0.41	637
	Autumn	492.46	561.60	69.14	14.04	0.19	0.05	0.15	744
	Winter	237.33	343.41	106.08	44.70	0.45	0.00	0.03	506
	Annual	399.28	470.44	71.17	17.82	0.25	0.08	0.14	681
Boluo	Spring	261.47	444.98	183.50	70.18	0.69	0.00	/	/
	Summer	1046.12	1069.81	23.69	2.26	0.14	0.12	0.31	1142
	Autumn	942.04	1026.83	84.79	9.00	0.13	0.05	0.20	1246
	Winter	342.88	469.68	126.80	36.98	0.37	0.00	0.05	741
	Annual	618.27	729.77	111.50	18.03	0.23	0.05	0.12	1280

of native species, and invasion of alien species. Improvement in water resource management is necessary to mitigate the negative impacts on the ecosystem and meet the requirement for adequate water supplies.

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