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Impacts of Climate and Human Activities on Hydrological Regime in Dongting Lake, China

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THESIS DECLARATION

I, Yahong Kuang, hereby declare that all work in this thesis, submitted in fulfilment of the requirements of the award of Master of Engineering Research, in the School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

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ABSTRACT

The natural flow regime is vulnerable to both climate variability and human activities. Therefore, understanding the hydrological alteration and the effects of climate and human factors is crucial for future water resources management and environmental sustainability. Dongting Lake, the second largest freshwater lake in China, is characterized by rapid changing hydrological conditions suffering from both climate and human impacts. The aim of this thesis is to examine the extent to which natural flow regimes have been changed in Dongting Lake under the combined effects of climate and human impacts, as well as to quantify the respective effects of climatic variabilities and human activities on streamflow.

The Indicators of Hydrologic Alteration are used to investigate the pre- and post-dam hydrologic changes in flow magnitude, frequency, duration, timing and rate of change at the annual, quarterly, monthly, weekly and daily scales. Results show that the natural flow regime in Dongting Lake has been changed noticeably following the regulations of Three Gorge Dam (TGD) and Gezhouba Dam (GD), and the changes become more significant after the regulation of TGD. The lake has suffered from long-term water resource losses with remarkably reduced annual flow after the impounding of the two dams. From January to March, the monthly flow has become marginally higher than the natural situation, while it is substantially dampened in the remaining nine months. There are minor magnitude increases in the daily, weekly, monthly and quarterly minimum flows, while significant decreases are identified in extreme high flow at various time scales. Besides, the timing of extreme water conditions, frequency and duration of high and low pulses have also been modified to different extents. Furthermore, the rates of both hydrograph rise and fall have been significantly reduced following TGD, whereas flow has become flashier with more frequent hydrograph reversals.

The Budyko-based decomposition and runoff sensitivity methods are used to quantitatively assess the respective impact of climatic variations and human activities on streamflow alteration over the five study regions. The two methods yield very close results that indicate that both climate and human activities are the combined driving factors that change the streamflow. During the first-impacted period (1982-2002), streamflow over Xiangjiang, Zishui, Yuanjiang, and the Whole basin increased to various extents while streamflow over Lishui decrease slightly. Climate change or variability acts as a decisive role in contributing 59.5%~72.3% of the total changes in annual streamflow, while human activities accounts for 27.7%~40.5%. During the second-impacted period (2003-2014), streamflow over all the five regions show a decrease resulted from both climate and human impacts, with human-induced and climate-induced changes in annual streamflow contributing 57.3%~72.2% and 27.8%~42.7% of the overall changes in annual streamflow, respectively.

To my dear uncle Dakun Zhang

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Yahong Kuang

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ABBREVIATIONS

TGD	Three Gorges Dam
GD	Gezhouba Dam
IHA	Indicators of Hydrologic Alteration
ET	Evapotranspiration
PET	Potential evapotranspiration
CV	Coefficient of variation
Q	Streamflow
P	Precipitation
ΔS	Change in water storage
E/P	Evapotranspiration ratio
E_p/P	Climatic dryness index
ΔQ^c,	Climate-induced streamflow
ΔQ^h	Human-induced streamflow
ΔP	Changes in annual precipitation
ΔE_p	Changes in annual potential evapotranspiration
$\frac{\partial Q}{\partial P}$	Streamflow sensitivity coefficient to precipitation
$\frac{\partial Q}{\partial E_P}$	Streamflow sensitivity coefficient to potential evapotranspiration

1 SIGNIFICANCE AND RESEARCH OBJECTIVES

1.1 Background

The flow regime of a catchment describes the magnitude, timing, frequency, duration and rate of change of flows (Poff et al., 1997). It plays an irreplaceably important role in maintaining the ecological integrity of rivers, lakes and wetlands (Poff et al., 2010). The natural flow regime depends on the climate, runoff, catchment size and geomorphology without human interventions such as reservoir regulation, extraction and river management. Thus, the natural flow regime is vulnerable to both climate variability (such as changes in temperature and precipitation), and anthropogenic changes including dam constructions, water use, and land cover modifications. The key climatic factors influencing the flow regime are precipitation and evapotranspiration rate, with the latter largely determined by temperature (Patterson et al., 2013). Meanwhile, direct human intervention and human-induced climate change also affect hydrological cycles and thereby induce streamflow alterations (Mittal et al., 2016).

Alteration of the natural flow regime of rivers, streams and lakes modifies the riverine habitat conditions, thus changes the distribution, diversity and abundance of riverine species. Flow regime changes, especially resulting from climate variabilities, are more likely to induce risks to catchment water resources management that includes water quantity problems (extreme drought and flood disasters), sedimentation problems and water quality problems. Therefore, understanding the alterations of flow regime is a fundamental aspect of characterizing, restoring and maintaining the ecological integrity as well as a significant reference to effective water resources allocation.

Dongting Lake, located in the middle reaches of the Yangtze River basin, is the second largest freshwater lake in China. The main lake area receives inflow from both the Yangtze

River and four tributary rivers, and it has only one outlet with all the water going out into the Yangtze River again. The Lake is characterized by very complex water system and complicated lake-river interaction between the lake and the Yangtze River. In several recent decades, it has gone through significant flow regime changes, especially severe flood and drought problems. Many researchers insist that the hydrological changes in Dongting Lake should be attributed to human activities, especially the two biggest dams in the world, Three Gorges Dam (TGD) and Gezhouba Dam (GD) (Ou et al., 2012, Sun et al., 2012, Feng et al., 2013, Zhan et al., 2015, Zhang et al., 2015a, Zhou et al., 2015). However, some researchers believe that hydrological changes in Dongting Lake are possibly linked to climate variability (Dai et al., 2008, Dai et al., 2010, Huang et al., 2014, Lai et al., 2014). It is still not clear how the flow regime in Dongting Lake has been changed by the combined effects of human and climate impacts, and how the two factors are responsible for the flow regime changes.

Although flow regime changes and the effects of climate variabilities and human activities have been examined for numerous regions across the world (Smith et al., 2005, Patterson et al., 2013, Ahn and Merwade, 2014, Renner et al., 2014), to our knowledge no comprehensive and quantitative assessment has been conducted on the alterations of the full ranges of the flow regime in Dongting Lake basin and its response to climate and human impacts. Therefore, this work focuses on the changes of the full ranges of flow regimes in Dongting Lake and the potential effects of climate variabilities and human activities on the natural flow regimes based on the sufficient observed hydrological, meteorological data and other catchment properties.

1.2 Research objectives

The main objectives of this thesis are to investigate the extent to which hydrological conditions have been changed in Dongting Lake under the combined effects of climate and human impacts, as well as to quantify the relative responses of streamflow to the changes in climatic variabilities and human activities. Therefore, the research work presented in this thesis has been carried out with the following specific objectives:

(1) To understand the observed historical climate and hydrological conditions in Dongting Lake;
(2) To characterize the natural flow regimes during the un-impacted period;
(3) To quantify the full ranges of flow regime changes in Dongting Lake with the hydrologic metrics of indicators of hydrologic alteration (IHA) during the two impacted periods;
(4) To distinguish the separate impacts of climate variabilities and human activities on streamflow using the Budyko-based decomposition and runoff sensitivity methods.

1.3 Research significance

As the second largest freshwater lake in China, Dongting Lake is the only spillway-type lake located in the middle reaches of the Yangtze. It serves multiple functions in environment and economics development, including Ramsar Wetland for wintering waterbirds, agriculture irrigation, water storage, flood prevention, and local climate regulation. Besides, Dongting Lake is the first big lake downstream the huge dam, Three Gorges Dam, therefore, it is the most vulnerable to hydrologic regime changes under upstream dam regulations among all the lakes within the Yangtze River Catchment. Hence, the study on how climate and human activities on flow regimes in Dongting Lake is of great value in every aspect.

In this work, the full ranges of flow regime changes in Dongting Lake and the potential effects of climate variabilities and human activities on the natural flow regimes are examined based on the sufficient observed hydrological, meteorological data and other catchment properties. Under the background of climate change and intensive human activities, this study helps enhance the comprehensive understanding of the flow regime characteristics of Dongting Lake during the recent 55 years (1960-2014), and the understanding the severity of impact due to human activities in view of climate change by distinguishing flow regime alterations induced by human activities from that caused by changing climate conditions. This study would provide significant reference to decision makers in water resources allocation, lake restoration, lake ecosystem management programmes in the future.

1.4 Thesis layout

The above specific objectives have been achieved and the details of current research are presented in the following chapters:

Chapter 2 presents an extensive literature review related to this study. Existing research on flow regime changes and assessment of climate and human impacts have been critically reviewed in this chapter. Meanwhile, the related studies on Dongting Lake have also been carefully reviewed.

Chapter 3 presents the detailed description of the study area, including the geographic location, climate and hydrological conditions, land use and human activities over the Dongting Lake.

Chapter 4 describes the division of the whole study period of 1960-2014 into one pre-impacted period of 1960-1981, and two post-impacted periods of 1982-2002 and 2003-2014. This chapter presents the observed natural streamflow during the pre-impacted period as well as streamflow changes during the two post-impacted periods. Moreover, the natural flow regimes and hydrologic shifts in the pattern, magnitude, timing, duration and direction of lake flow are investigated on annual, quarterly, monthly, weekly and daily scales, based on the hydrologic metrics of indicators of hydrologic alteration (IHA).

Chapter 5 descibes the Budyko-based decomposition and runoff sensitivity methods used in this study, as well as the assumptions made for this study. The relative responses of streamflow to the changes in climatic variations and human activities for the sub-basins as well as the whole Dongting Lake basin are examined, and the results of the two methods are compared and discussed.

Chapter 6 presents the summary and conclusions of this thesis. In addition, recommendations for further research are also given.

2 LITERATURE REVIEW

2.1 Introduction

Streamflow is an essential component of water resources throughout the world, yet it has been profoundly influenced by both climate change and human activities at local, regional and global scales (McCabe and Wolock, 2002, Chiew et al., 2009, Déry et al., 2009, Tomer and Schilling, 2009, Piao et al., 2010, Al-Faraj and Scholz, 2014, Renner et al., 2014, Tan and Gan, 2015). Climate change, including shifts in precipitation, temperature, air humidity, and wind speed, could be the primary determinant that affects the quantity and pattern of streamflow directly or indirectly (Campbell et al., 2011, Ye et al., 2013). Human activities, on the other hand, might alter streamflow indirectly via effects on climate (e.g. greenhouse gas emissions) or directly via changes in the landscape or infrastructure (Zheng et al., 2009, Patterson et al., 2013, Renner et al., 2014). While many studies have revealed that climate and human activities jointly affect the streamflow, it is highly necessary to explicitly quantify how streamflow responds respectively to the changes in climate variables and human activities. Such information provides important insights into future water resources planning and management regarding accurate prediction and effective coping with anticipated changes in streamflow suffering from climatic and human impacts.

This chapter presents a review of existing knowledge related to the hydrological alteration. As pointed out in Chapter 1, the flow regime of a river or lake can easily be affected by climate variability and human intervention. Therefore, in the remaining chapter, existing knowledge of the relationship between streamflow and climate variations and human activates, as well as how natural streamflow is altered by the aforementioned two factors have been well reviewed. Meanwhile, an overview of existing methods of separating climate and human impacts are also given. Furthermore, existing literature reviews on flow regime changes in Dongting Lake have been carried out.

2.2 Hydrologic patterns and flow regimes

The streamflow response to rainfall is affected by many attributes, including the area's climate, topography and geomorphology (Poff et al., 1997, Snelder et al., 2009), which account for hydrological processes of precipitation, snowmelt flow, surface runoff and groundwater runoff. The complex interactions between these attributes and the natural hydrological processes induce complexity in hydrology, thus cause variability of streamflow in space and time (Sivapalan, 2006).

River flow regimes describe the temporal patterns of flow variability. They can be described by five streamflow components: magnitude, frequency, duration, timing, and rate of changes of flows (Poff et al., 1997). Magnitude describes the amount of water moving past a fixed location per unit time. Frequency, also described as exceedance probability, describes how often a flow above a certain magnitude recurs over some specific time interval. The exceedance probability can be calculated by a statistical analysis based on a continuous dataset of flows and can be illustrated by the flood frequency curve. Duration is the period of time relative to a specific flow condition, which can be defined associated with a particular flow event or a composite described over a specified time period. Timing refers to the occurrence of flows within the annual hydrologic cycle. Detection of significant shifts in timing is important, especially the timing of peak and base flows, which have ecological significance. Rate of change describes how quickly flows change from one magnitude to another. The two extremes of rate of change are flashy (unstable) or stable (slow) (Poff et al. 1997).

The flow regime has played a vital role in the hydrological, environmental and ecological aspects in understanding streamflow variability under changing climate conditions and human activities, exploring accurate environmental monitoring, and proposing effective water allocation decisions. The five hydrologic metrics describing the full range of flow regimes have been extensively used throughout the world to address hydrological, environmental and ecological questions. There exist diverse studies on flood frequency estimation and drought assessment (Cunderlik and Ouarda, 2009, Al-Faraj and Scholz, 2014, Zhang et al., 2016a), characterization of the spatial variation of flow regimes (Richter et al., 1998, Hannah et al., 2005, Ryo et al., 2015), hydrologic model calibration and validation (Bradford et al., 2007, Zhang and Döll, 2008, Shrestha et al., 2014), detection of flow regime alterations by human intervention and under changing climate conditions (Hu et al., 2008, Suen, 2009, Mittal et al., 2014, Chen et al., 2015), hydrologic trend detection (Yue et al., 2003, Zhao et al., 2010, Meitzen, 2016), environmental flow assessment (Poff et al., 2010, Poff and Zimmerman, 2010, Zhang et al., 2014c), and investigation of hydrological changes on biological and ecological processes (Neff et al., 2009, Worrall et al., 2014, Kozak et al., 2015).

The streamflow characteristics can be reflected from various aspects of flow regimes, including the seasonal patterns of flows, the timing, frequency and duration of extreme flows, the flow variability at different time scales. To characterize different aspects of flow regimes, a number of hydrologic indices have been developed by researchers. In the early studies, researchers mainly focused on average flow conditions, seasonal distributions of monthly flows, flow and flood frequency duration curves, and variations of annual discharge (Murray, 1887, Hawkes et al., 1986, Tiao, 1990, Waylen and Caviedes, 1990, Gan et al., 1991, McMahon et al., 1992). More recent studies have focused on adopting multivariable approaches to develop and apply sets of hydrologic indices simultaneously to quantify hydrologic regimes (Richter et al., 1996, Poff et al., 1997, Wilcox et al., 2002, Gao et al., 2009, Ghanbarpour et al., 2013). To date, there exist over 171 hydrologic metrics capturing various aspects of the streamflow attributes. Clausen and Biggs (2000) investigated 35 flow variables including general flow variables (e.g. Mean flow and coefficient of variation), high flow variables and low flow variables for 62 New Zealand rivers, and recommended that a suite of different variables representing the size of the river, the overall variability of flow, the volume of high flows, and the frequency of high flow events should be used in riverine hydrologic and ecological studies.

Olden and Poff (2003) examined 171 hydrologic indices using the long-term flow records obtained from 420 sites across the continental USA and provided some statistically and ecologically based recommendations in selecting hydrological indices. Their results show that the Indicators of Hydrologic Alteration (IHA) method proposed by Richter et al. (1996) stands out well compared with other indices. IHA software (Richter et al., 1996, The Nature Conservancy, 2009) is a Windows-based computer software and can calculate a suite of 33 individual hydrologic metrics describing the full ranges of flow regimes: magnitude of monthly streamflows, magnitude and duration of annual extreme flows, timing of annual extreme flows, frequency and duration of high and low pulses, rate and frequency of flow changes (Mathews and Richter, 2007). IHA adequately captures the majority of the information explained by the 171 indices and represents the major components of flow regimes, therefore strike a good balance between selection of sufficient information indices and accessibility of computation (Olden and Poff, 2003). The suite of IHA indices has been extensively used in assessing the degree of ecologically relevant hydrologic alteration to natural flow regimes from daily to monthly time scales, optimizing environmental flows, implying streamflow variabilities in prediction of aquatic species (Belmar et al., 2013, Al-Faraj and Scholz, 2014, Worku et al., 2014, Worrall et al., 2014, Chen et al., 2015). Especially, IHA has been world-widely used in assessment of hydrologic alterations related to dam constructions, e.g. the East River in the Pearl River basin in China (Zhang et al., 2014c), Tajan River Watershed in Iran (Ghanbarpour et al., 2013), the Upper Mississippi River System (Theiling and Nestler, 2010), four hydropower sites in the USA , the upper Srepok River basin in Vietnam (Van Ty et al., 2011). According to various objective selections of riverine and ecological managements, different small subsets of hydrologic indices from IHA have been selected. For example, Yang et al. (2008c) identified 6 (date of minimum, rise Rate, number of reversals, 3-day maximum, 7-day minimum and May flow) out of the 33 IHA indices as the most ecologically relevant hydrologic indicators in studying fish diversity and abundance. In this thesis, the suite of IHA indices is to be adopted to analyse the flow regime alterations during the post-dam period in Dongting Lake basin.

2.3 Impacts of climate change and variability on flow regimes

Under the global background of climate change, the average temperature of the earth's surface in China has risen by 1.1 degrees Celsius over the past century (1908-2007) and is estimated to have annual average temperature rise by 3.5 degrees Celsius by the end of the 21^{st} century. Climate change is a significant long-term shift or change in weather conditions identified by changes in temperature, precipitation, winds, and other indicators which usually persist for decades or even longer (IPCC, 2007). Climate variability includes all forms of fluctuations of the climate system (i.e. deviations from long-term statistics) and can be considered as a natural phenomenon and happens occasionally from time to time (e.g. a month, season or year). Climate change is the longer term change on the decades or century timescale and climate variability is variability on shorter timescales, which can arise from internal processes like ENSO or external sources like solar variability.

Changes in streamflow characteristics can be influenced by climatic factors (Mittal et al., 2014, Rouillard et al., 2015, Zhang et al., 2015b). Climate change and variability may cause hydrological changes include earlier snowmelt, change in streamflow timing, altered maximum and minimum flows, and intensified floods and droughts (Adam et al., 2009, Kyambia and Mutua, 2015, Van Loon and Laaha, 2015). According to the Intergovernmental Panel for Climate Changes (IPCC) Fifth Assessment Report, anthropogenic climate change is very likely to lead to increases in the intensity and frequency of temperature and precipitation extremes (IPCC, 2014), thus may alter hydrological processes including evapotranspiration, surface runoff, timing and magnitude of streamflow, and flood events (van Pelt and Swart, 2011, McLaughlin et al., 2014).

In recent decades, the impact of climate change and variability on streamflow has been well documented, and many studies showed that the variations of precipitation, evaporation and temperature may alter streamflow (McCabe and Wolock, 2002, Dore, 2005, Chang et al., 2015, Kyambia and Mutua, 2015, Kibria et al., 2016). Precipitation is the main cause of variability in the water balance at temporal and spatial scales, and changes in precipitation are the most important climatic variable influencing streamflow. Changes in precipitation in terms of the intensity, duration and distribution may induce great variability in flooding, such as floods of longer duration, or floods of greater magnitude but shorter duration. It has been documented that climate change and variability, especially due to precipitation, temperature, evapotranspiration and sea level change, can attribute to the changes in the magnitude and frequency of flooding (Bronstert et al., 2002, Trenberth, 2006, Mallakpour and Villarini, 2015).

In addition, both changes in precipitation and evaporation are strongly influenced by changes in temperature. Potential evapotranspiration (PET) indicates the amount of evaporation that would occur if a sufficient water source were available. An increase in temperature can cause an increase in the vapor pressure deficit, resulting in a decrease in relative humidity and an increase in PET. Thus, the increase in PET results in an increase in evapotranspiration (ET) rate, which indicates higher available moisture levels permit.

2.4 Impacts of human activities on flow regimes

This section reviews the facts that natural flow regime changes under human activities, and how it might be affected under different types of human activities, including urbanization, land use/cover changes, and structure interventions (such as water withdrawal, hydraulic construction and operation, et al.). Moreover, this section presented the impacts of dam constructions on natural hydrologic regimes all over the world and the consequences of flow regime alterations.

Streamflow is the flow of water in streams, rivers, and other channels, which is a complex process of water cycling through the atmosphere, land cover, soils, and geologic formations, therefore, except for the changes in climate change and variability, human activities also affect the streamflow in respect to the spatial and temporal patterns (Naik and Jay, 2011, Ahn and Merwade, 2014, Wang et al., 2015). Global river systems have been experiencing significant changes under anthropogenically driven changes like water abstractions, land cover changes, and hydraulic structure constructions (Peters and Prowse, 2001, Batalla et al., 2004). In many areas of the world, streamflow is being increasingly affected to some extent by the influence of human activity. Cultivation, urbanization, and other such human activities mainly affect the hydrologic processes via land use/cover changes (Lørup et al., 1998, Mango et al., 2011, Tran and O'Neill, 2013, Neupane and Kumar, 2015, Kibria et al., 2016), therefore, have indirect effects on streamflow. It is proved that land use/land cover changes can alter the ET, groundwater discharge, and surface runoff (Niehoff et al., 2002, Huntington, 2006, Liu et al., 2015, Kibria et al., 2016).

Whether flow is increased or decreased depends on the type of human activity. For example, urbanization tends to result in lower infiltration capacity through expanded impermeable surfaces such as roads and buildings, and thus precipitation is re-captured by artificial structures in the form of direct runoff, which rapidly converts into stream. Usually, the streamflow, being moderated by the high infiltration rate, will increase to a certain level and then drop back to the base level. As urbanization increases the amount of impervious surface, the infiltration is limited by the expanse of impervious surfaces, thus results in lower base flow and higher peak flows and volumes. Fig. 2.1 shows that the hydrographs before and after urbanization undergoes changes in both timing and magnitude, and indicates that the rising and recession limbs of storm hydrographs become higher and steeper for urbanized streams than that for non-urbanized streams, due to faster and greater runoff and decreased infiltration.

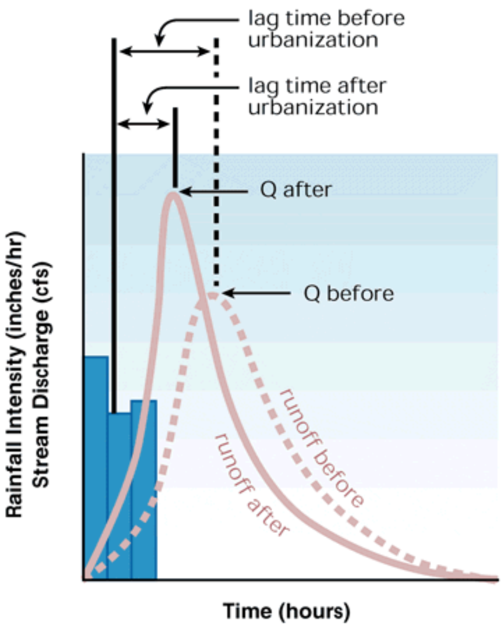


Fig. 2.1 A comparison of hydrographs before and after urbanization (blue bars indicate rainfall rate and timing).

(https://cfpub.epa.gov/watertrain/moduleFrame.cfm?parent_object_id=624&object_id=629)

It is an evidence that in monsoonal Sri Lanka, the conversion of tea plantations to other types of land use without appropriate soil conservation measures in the upper Mahaweli catchment, can attribute to a decrease in dry season flows (Bruijnzeel, 2002). It is stated that the inappropriate soil conservation measure accounts for 74% of the total reduction in mean annual streamflow in a small catchment in the Loess Plateau (Zhang et al., 2014a). In the Araguaia River in east-central Brazil, 55% of the native vegetation has been removed because of the deforestation, which has significantly modified the hydrological and morphological characteristics. The increased discharge from 1970s to 1990s was more ascribed to the deforestation than climate variability (Coe et al., 2011).

By comparison, water withdrawal, hydraulic construction and operation, and other such human interventions have a direct impact on the spatial and temporal distribution of streamflow (Ren et al., 2002, Assani et al., 2006, Adam et al., 2007, Yang et al., 2008b, Piqué et al., 2015). According to the global-scale analysis on river flow alterations resulted from water withdrawals and reservoirs, areas most affected are the Western and Central USA, Mexico, the western coast of South America, the Mediterranean rim, Southern Africa, the semi-arid and arid countries of the Near East and Western Asia, Pakistan and India, Northern China and the Australian Murray-Darling Basin, as well as some Arctic rivers (Döll et al., 2009). Among the aforementioned human activities, medium to large impoundments have significant impacts on flow regimes in terms of the timing, magnitude, and frequency of high and low flows, which ultimately cause significantly differences between the impaired and the un-impaired natural situations (Magilligan and Nislow, 2005). Downstream flow regime has been widely acknowledged to be affected by large impoundments (Batalla et al., 2004, Nilsson et al., 2005, Graf, 2006, Wang et al., 2013a). Of all large impoundments, the regulation of dams has the most pervasive and damaging effects on hydrologic regime shifts, producing flow characteristics significantly different from the pre-impoundment natural flow regime (Batalla et al., 2004, Magilligan and Nislow, 2005). The Zambezi Basin, being the fourth largest in Africa, has suffered from considerable hydrological changes in terms of seasonal pattern, the magnitude, and the frequency following the dam impoundments in the Zambzi and its main tributaries (Matos et al., 2010). Under the regulation of High Aswan Dam across Nile River, the flowrate and flow level downstream the dam has been changed throughout the year with an sharp decrease in the flowrate (Raslan and Salama, 2015).

Numerous studies on flow alteration by dam regulation can be found both at global scale and basin scale. Nilsson et al. (2005) reported that more than 50% of global large river systems have been affected by dam regulation, including the eight most biogeographically diverse. Graf (2006) concluded that the natural hydrologic and geomorphic regimes of 72 American large river reaches have been altered to varying degrees by the 36 largest dams. Hu et al. (2008) demonstrated the downstream hydrologic regime has been strongly affected by dams in the Huaihe River basin, China, especially in dry seasons. Conceivably, precisely how regulated flow differs from natural conditions significantly depends on the capacity of a dam, its operational purpose (e.g. hydroelectric generation, irrigation diversions, flood control), and operational modes. According to Graf (1999), the impacts of dams on flow regimes across the continental U.S. is several times greater than the impacts of global climate change. Fitzhugh and Vogel (2011) confirmed that flood flow has been altered in every region of the continental U.S., especially in the southern Great Plains, desert Southwest, and north California. In the NW Mediterranean region, most of the twelve basins have been confronted with hydrological alterations, with special influence on monthly flows and flood magnitude and frequency (Piqué et al., 2015). A large proportion of natural wetlands wetlands in New England Tablelands of north New South Wales (NSW) in Australia have greatly changed in types and abundance because of the greatly altered water regimes through damming and draining (Brock et al., 1999). Mims and Olden (2013) demonstrated the hydrological and biological situations have been significantly changed by the river regulation by large dams in the United States.

In China, dams are a pervasive component of the river system in China, which segment the rivers and fragment the watersheds. Almost 70% of the total annual discharge has been regulated by 98,000 nationwide reservoirs with varying sizes (Yang et al., 2016). Both the Yangtze River and the Yellow River, which are the two longest rivers in China, have suffered from significant flow regime changes from human activities, especially dam constructions (Zhao et al., 2004, Gao et al., 2013). In the Yangtze River (1.94 million km^2), the third longest river in the world, more than 45,700 dams with a total capacity of 220.0×10^9 m^3 have been constructed (Yang et al., 2009). The Yangtze River, thus, has been confronted by drastic flow regime changes (Yin and Li, 2001, Gao et al., 2012, Zhang et al., 2013). It is well acknowledged that the flow regimes in the middle and lower Yangtze River have been significantly affected by the upstream dam regulations (Yang et al., 2008b, Wang et al., 2014, Zhang et al., 2014d, Dai et al., 2015), especially one of the world's biggest dams, Three Gorges Dam (TGD) and China's previously biggest dam, Gezhouba Dam (GD). Considering its large capacity, TGD has resulted in great concern over altering flow regime downstream since the beginning of water impoundment in the middle reach of the river in 2003 (Dai and Liu, 2013, Wang et al., 2013a). Meanwhile, it is evident that irrigation has not only depleted streamflow but also changed the flow pattern and seasonal variability (Zeng and Cai, 2014). In the Shiyang river basin in northwest China, human activities, such as irrigation, account for 60% of total flow decreases of the upstream flow in the 1970s (Huo et al., 2008).

The consequences of flow regime alterations resulted from dam operations have been well documented. By changing the flow characteristics, the sediment transport capacity is affected, thus the morphological process is inevitably changed (Li et al., 2011, Yuan et al., 2012, Raslan and Salama, 2015). It is reported that many deltas worldwide, including the Colorado delta in the USA, Nile delta in Egypt, the Yellow River and the Yangtze River deltas in Chian, have been confronted with recession problem due to the construction of dams (Yang et al., 2005). On the other hand, the alteration of flow regime by dams has been widely recognized as important factor that damages the biological diversity and ecological functions in aquatic ecosystems (Zeilhofer and de Moura, 2009, Poff and Zimmerman, 2010, Chen et al., 2015). Ziv et al. (2012) estimated the dish biomass and biodiversity losses in various damming scenarios in the Mekong River Basin, and found that the completion of 78 dams on the tributaries would have devastating impacts on fish productivity and biodiversity and called for careful reassessment of the dam projects. The ecologically important streamflow changes have profound implications for the native species in the riverine and floodplain, and also for effective river ecosystem management through better understanding and predicting the potential impact of flow regime alteration on riverine biota. Yet despite the recognition of the importance of streamflow to both fluvial geomorphology and stream ecology, there is little agreement in quantifying how much of the streamflow changes are attributed to human activities and climate variations, respectively. Many dam protesters ascribe streamflow changes entirely to human activities without considering factors like precipitation and evaporation, while meteorologists might emphasize the role of meteorological factors regardless of human impacts. Such lack of taking both human impact and climatic factor into consideration appears to be a key limitation in accurately quantifying what roles that human activities and climate variations play in streamflow changes. Therefore, research on distinguishing the impacts of human activities and climate variations on streamflow is needed to enhance our knowledge of climate adaption, human activity optimizing and watershed management.

2.5 Methods of separating climate and human impacts on flow regimes

A number of attempts have been made to distinguish climate and human influences on streamflow at catchment scales (Mango et al., 2011, Murphy and Ellis, 2014, Gyawali et al., 2015) and at national scales (Sankarasubramanian et al., 2001, Renner and Bernhofer, 2012, Tan and Gan, 2015) by employing complex numerical models including hydrologic modelling, regression model, and water-energy balance approaches. There exist numerous studies investigating the impact of climate changes by varying the climatic inputs to the calibrated numerical models and comparing the resulting differences in streamflow (Xu, 1999, Christensen et al., 2004, Arnell and Gosling, 2013, Anis and Rode, 2015). Also, some studies have coupled hydrological model with global climate models to determine the potential impacts (Quilbé et al., 2008, Gain et al., 2011, Thompson et al., 2013). Traditionally, many studies apply the hydrological modelling approach to analyse the streamflow sensitivities to climate and human effects, such as SIMHYD (Chiew et al., 2009), TOPMODEL and VIC models (Chang et al., 2015). Although the numerical modelling approach might be physically sound, it should be aware that those models might also have their own uncertainties associated with model structure, parameter calibration, scale problem and other application conditions. It is not always possible to achieve reliable results when the model is not chosen suitably and parameters are not calibrated properly (Sankarasubramanian et al., 2001, Chiew, 2006, Jones et al., 2006, Vaze et al., 2010, Zhang et al., 2011).

The regression approach provides an alternative choice in analysing streamflow response to changes in human and climate conditions. Ye et al. (2003) established the monthly streamflow relationships between upstream and downstream stations before the operation of the reservoir, and developed a simple linear regression for monthly and yearly flows as a function of time/year to detect the trend differences and quantify the changes induced by natural variations and human impacts within the Lena watershed. Some studies have quantified the effect of human activities and climate variations on flow changes by adopting regression approach to develop a linear multi-regression among streamflow, human factors, and climatic variables. Huo et al. (2008) developed a multi-regression among streamflow, precipitation and temperature to determine the flow change in the absence of human activities in the Shiyang river basin in arid north-west China. Jiang et al. (2011) related monthly runoff to monthly precipitation and PET during the natural period through the multi-regression method, and reconstructed the natural runoff to separate the impact of human activities during the human induced period. Although the regression is easy and convenient, the result is not always reliable under the non-linear conditions and it is difficult to consider all the impact factors, especially changes induced by various human activities.

Recently, the Budyko framework (Budyko, 1974) regarding to the concept of water and energy constraint over a long-term timescale, is well-established to have the potential to efficiently distinguish the impacts of climate change and human activities on streamflow changes (Yang et al., 2008a, Wang and Hejazi, 2011, van der Velde et al., 2014). The Budyko framework describes an empirical global relationship between the evaporation ratio and climatic dryness (or aridity) index, in which the evaporation ratio is defined as the ratio between mean annual actual evapotranspiration and mean annual precipitation, and the dryness (or aridity) index is defined as the ratio of mean annual potential evapotranspiration to mean annual precipitation. This relationship implies that for long timescales, the equilibrium water balance is primarily constrained by water availability and atmospheric demand. Typically, two methods based on the Budyko framework have been developed to assess the impacts of climate change and human activities on streamflow, namely runoff sensitivity (or elasticity) method and decomposition method. The Budyko-based sensitivity or elasticity method quantifies the sensitivity of streamflow to either climate change or human activities by calculating the sensitivity coefficients of runoff to precipitation and potential evaporation (Schaake and Liu, 1989, Schaake, 1990, Roderick and Farquhar, 2011). The Budyko-based decomposition method proposed by Wang and Hejazi (2011) is another reliable method to explicitly quantify the relative contributions of climate and human activities to the changes in streamflow. There are some differences between the two Budyko-based methods. The decomposition method can independently estimate the individual responses of streamflow to direct human and climate change by treating the climate dryness index as one component, while the sensitivity method usually first calculate the climate impact and then the human impact by separately computing the sensitivity coefficients of precipitation and potential evaporation to streamflow (Wang and Hejazi, 2011, Jiang et al., 2015).

Compared to hydrological modelling approach, the two Budyko-based methods require less observed hydro-climate data. Daily and monthly data are not necessary if long-term average annual precipitation and potential evaporation data are available. Moreover, the two methods can be applied to compare the streamflow responses over different time periods within the same study area or across different catchments during the same period (Donohue et al., 2011, Wang and Hejazi, 2011). These two Budyko-based methods have been widely used in various study areas in attribution analysis of climate variation and human activities to streamflow alteration. Roderick and Farquhar (2011) applied the Budyko-based sensitivity method to accurately predict the long-term evapotranspiration and runoff over in the Murray-Darling Basin in southeast Australia and successfully related the variations in runoff to variations in climatic conditions and catchment properties. Patterson et al. (2013) successfully used the Budyko-based decomposition method to ascribe changes in streamflow due to climate and human factors between two time periods in both natural and human-modified basins in the South Atlantic, USA, and found that climate variability tended to have more impact on streamflow changes than human variability did over shorter time periods. Gardner (2009) adopted the Budyko-based sensitivity method to assess the effects of climate change on river runoff over various basins and concluded that this method favourably yielded similar results with those based on more complex hydrological models and those based on long-term historical observations of runoff and climate variations.

2.6 Hydrological changes in Dongting Lake, China

Lakes, natural or artificial, are important for the preservation of ecosystems and biodiversity, as well as for human existence. Lakes, accounting for 68% of the liquid freshwater on the earth's surface (Beeton, 2002), have played critical roles in the water cycle. They are important in sustaining aquatic biodiversity, as well as in the economies and social structure. Despite of the significance of lakes, many lakes around the world are shrinking or disappearing, and the overall conditions of the remaining lakes are deteriorating because of natural events (e.g., climate change and soil erosion) and anthropogenic factors (e.g., over-reclamation and misguided management policies) (Bradley, 2001, Xie et al., 2010). The Lake Chad basin, the world's largest endorheic basin, shrank from 22,000 km^2 to about 300 km^2 from the 1960s to the 1980s (Singh et al., 2006). The Yangtze River Basin in China, has the most representative and largest concentration of freshwater lakes in China with up to 100 lakes (area ⩾10 km^2) covering a total area of 10,593.4 km^2, accounting for 38.17% of the total area of all freshwater lakes in China. However, these lakes are vulnerable to floods and droughts. During 1951~1978, the probability of flood and drought events in the Yangtze River Basin was 43% and 48%, respectively (Zhang et al., 2008), which cause lots of flood and drought problems for the lakes.

Among them, the second largest lake, Dongting Lake, has experienced significant changes in recent several decades. To date, numerous studies have reported that the lake has experienced flow condition changes, including changes in the river-lake relation between the Yangtze River and Dongting Lake (Dai et al., 2005, Yin et al., 2007, Chang et al., 2010, Ou et al., 2014), shrinkage of lake area (Zhao et al., 2004, Li et al., 2007, Nakayama and Watanabe, 2008, Du et al., 2011), frequent flood and drought disasters (Yin et al., 2007, Xue et al., 2012, Huang et al., 2014), changes in lake area-water level relationship (Peng et al., 2005) and wetland inundation pattern (Lai et al., 2013, Deng et al., 2014, Hu et al., 2015). Many studies relate these changes to human effects, especially upstream TGD impoundment in recent ten years (Ou et al., 2012, Sun et al., 2012, Feng et al., 2013, Zhan et al., 2015, Zhang et al., 2015a, Zhou et al., 2015). However, a number of studies argue that the hydrological changes in the middle reaches of the Yangtze River basin including Dongting Lake are more likely to be affected by climate variability (Dai et al., 2008, Dai et al., 2010, Huang et al., 2014, Lai et al., 2014).

As Dongting Lake is the first lake downstream of TGD and GD, it has been inevitably affected by upstream dam regulations. The lake has been changed from a siltation-dominant state during the pre-TGD period to an erosion-dominant state after the impoundment of TGD (Sun et al., 2012, Zhou et al., 2015), and the river-lake interaction between the Yangtze River and Dongting Lake has been altered with weakened water supply from the river to the lake and enhanced water replenishment from the lake to the river (Chang et al., 2010, Ou et al., 2014, Zhang et al., 2015a). Meanwhile, the water level has been modified under different dam operational modes (Ou et al., 2012, Lai et al., 2014, Yuan et al., 2015), and the temporal and spatial inundation patterns have been affected by the operation of TGD (Feng et al., 2013, Lai et al., 2013). As such, these changes not only significantly contribute to the changing wetland landscape patterns by affecting the growth and the distribution of wetland vegetation communities (Hu et al., 2015a, Hu et al., 2015b, Xie et al., 2015), but also exert great impact on the endangered migratory waterbirds and fish (Guan et al., 2014).

However, other studies argue that both climate variability and human activities should account for the discharge changes within the Yangtze River basin, including Dongting Lake. Dai et al. (2008) analysed the runoff in the Yangtze River basin during the extreme drought year 2006, and concluded that the impounding of TGD contributed 9% of the runoff loss while the extreme climate accounted for 45%. Dai et al. (2010) also concluded that the variation of baseflow discharge in the Upper Yangtze River Stream was greater than that in the Middle and Lower Yangtze River Stream with more intensive human. Although the baseflow was influenced by both extreme climate and human intervention, extreme climate was the dominant factor accounting for 90% in the extreme drought year 2006.

Although the above studies have documented the possible hydrologic changes in Dongting Lake, most of the studies simply compared the flow conditions before and after the impoundment of TGD regardless of the potential regulation impact of GD. Without more detailed investigation of the impacts of climate and human factors on the flow regime changes in Dongting Lake under the operation of the aforementioned two dams with sufficient observed data and the most recent data, no consistent sound conclusion can be obtained. There exists a firm debate between Feng et al. (2013) and Song and Ke (2014) on whether the dramatic flow changes over Dongting Lake and Poyang Lake was caused by TGD or the natural process of climate variation. Feng et al. (2013) believed that the dramatic decreasing trend in the inundation area of the two big lakes during 2000-2009 was highly attributed to TGD, while Song and Ke (2014) argued that the adopted 10-year data was insufficient to derive reliable long-term trends of flow change, and different conclusion was obtained when the data extended to 2010. Furthermore, no existing study has delineated the full range of the flow regimes, which is characterized by five critical hydrologic components (magnitude, frequency, duration, timing, and changing rate of hydrologic conditions). It is clear, however, that the full range of hydrologic regime is essential for describing the overall flow characteristics and specific hydrologic phenomena like floods and droughts, as well as the ecological consequences of modifications by human activities (Poff et al., 1997, Richter et al., 1997). Moreover, as a Ramsar wetland of international importance, the native biodiversity and integrity of aquatic ecosystem in Dongting Lake is sensitively affected by any of the aforementioned hydrologic metrics (Zhang et al., 2014b, Wu et al., 2015a).

Apparently, while existing studies on the streamflow changes in Dongting Lake are mainly focused on the trend analysis and the possible linkage between streamflow changes to changes in human activities or climate variables, the relative importance of climate variabilities and human activities on streamflow changes have not been explicitly investigated.

Recently, Yuan et al. (2016) quantified the relative impacts of climate and human activities on streamflow in the main Dongting Lake area using the runoff sensitivity (or elasticity) method under the Budyko framework. Their work is useful in understanding how much of the streamflow is affected from human effects versus climate impacts in the main Dongting Lake area, whilst there are some corrections and limitations that need to be addressed. The three analysis periods are determined based on their previous work (Yuan et al., 2015), in which the authors described the Mann-Kendall trend test (Kendall, 1975, Hamed, 2008) in data analysis section, while adopted the Mann-Kendall Abrupt test (Friedrich-Wilhelm and Peter, 1999, Zhang et al., 2006) rather than the Mann-Kendall trend test in the results section. Furthermore, the breakpoint is reliablely determined when the intersection of the direct and retrograde curves occurs within the confidence interval. It should be noted that if the intersection is beyond the confidence interval, the intersection can not be identified as the reliable abrupt point without further check (Tong Ji-Long, 2014). Besides, the trend should be insignificant instead of significant at the significance level of α if the absolute value is lower than the critical value of the standard normal distribution with a probability exceeding $\alpha/2$ for the two-tailed test (Sneyers, 1990). Thus in the study of Yuan et al. (2015), 1980 is the abrupt change year, while 2002 still need to be confirmed with other methods. And the changing trends of water level during the periods of 1961-1980 and 1981-1997 should be insignificant rather than significant whilst the increasing trend after 1997 whould be significant instead of insignigicant. Furthermore, actual evaporation for open-surface can be estimated by combining pan evaperation data with an appropriate pan coefficient or according to the empirically derived relationships (Kahler and Brutsaert, 2006, McMahon et al., 2013). In the study of Yuan et al. (2016), further discuss is required when the authors took the pan evaperation observed at the meteorological stations as the actual evapotranspiration.

2.7 Summary

Flow regimes play an important role in shaping the biophysical attributes and functioning of river and lake systems. Researchers often describe flow regimes with the five hydrologic metrics: magnitude, frequency, duration, timing, and rate of changes of flows. As natural flow regimes depend on the area's climate, topography and geomorphology, it is vulnerable to climate change and variability. Climate change and variability including variations of precipitation, evaporation and temperature can alter hydrological processes, thus flow regimes can be altered in terms of part of or all of the five hydrologic metrics. Meanwhile, human activities like water abstractions, land cover changes, and hydraulic structure constructions can also change the streamflow in respect to the spatial and temporal patterns. A number of approaches including numerical modelling methods, regression model, and water-energy balance approaches have been developed to isolate the impacts of climate and human activities on streamflow changes. Although the numerical modelling approach might be physically sound, it possesses uncertainties relative to model structure, parameter calibration, scale problem and other application conditions. On the other hand, the regression model is easier and more convenient compared with the numerical modelling approach, it can neither always achieve reliable simulation results. By contrast, the Budyko-based runoff sensitivity (or elasticity) method and decomposition method have more advantages in requiring less observed hydro-climate data and can be used to compare the streamflow responses over different time periods within the same study area or across different catchments during the same period.

This chapter also has a comprehensive review on hydrological variability in Dongting Lake, China. There are some studies insist that the flow regime alteration is attributed to frequent and obvious human activities, especially upstream dam impoundment, while other studies argue that the flow regime changes should be induced by climate variability. There are numerous studies on the phenomenon of flow regime changes in particular aspects, while research on the full range of flow regime characteristics and the quantification of separate impacts of climate and human activities on flow regime changes in Dongting Lake is sparse. In view of the importance, more research is needed. Therefore, the primary objective of the following research is to examine the full range of streamflow variability in Dongting Lake in recent 55 years (1960-2014), and distinguish flow regime alterations induced by human activities from that caused by changing climate conditions.

3 DESCRIPTION OF THE STUDY AREA

3.1 Introduction

Dongting Lake basin (Fig. 3.1), situated between 24º38′and 30 º26′N, and 107º16′ and 114 º17′E, is in the middle reaches of the Yangtze River basin in the central China. It has complicated geographical characteristics with mountain land for the west part of the basin of 200-1000m above the sea level, with hill for the south part of the basin of 50-400m above the sea level, and with plain for the north part of the basin of 25-50m above the sea level. It covers a drainage area of 262×10^3 km^2, accounting for 14% of the whole area of the Yangtze River basin. Dongting Lake is the second largest freshwater lake in China and the first off-stream lake downstream of the Three Gorges Dam. Dongting Lake has a water surface area of 2,625 km^2 and volume of 16.7×10^9 m^3, representing 21% surface water resource for the Yangtze River (HBCWRC, 1997). The Lake is characterized by very complex water system and complicated lake-river interaction between the lake and the Yangtze River. It has four river tributaries, namely, Xiangjiang, Zishui, Yuanjiang and Lishui (Four Rivers), with corresponding drainage area of 94.6×10^3 km^2, 28.1×10^3 km^2, 89.2×10^3 km^2 and 18.5×10^3 km^2, respectively. The four river tributaries contribute 61.3% of the total inflow in Dongting Lake during the period 1960-2014, of which 39.2%, 13.7%, 38.4%, and 8.7% of the flow comes from Xiangjiang, Zishui, Yuanjiang and Lishui, respectively. Besides, 28.3% of the total inflow comes from the three distributary channels, Songzikou, Taipingkou, Ouchikou (Three Channels), which are naturally connected to the Yangtze River. Flow coming from the four rivers, three channels and other sources finally drains back into the Yangtze River through the only outlet, Chenglingji, which results in a complicated river-lake interaction. As the only outlet of the lake, Chenglingji gauging station (Fig. 3.1(b)) is commonly adopted as the controlling station for the whole Dongting Lake (Peng et al., 2005, Han et al., 2016). The whole Dongting Lake basin can be divided into 5 sub-basins, Xiangjiang, Zishui, Yuanjiang, Lishui and the Main Lake, as indicated in different colours in Fig. 3.1(a).

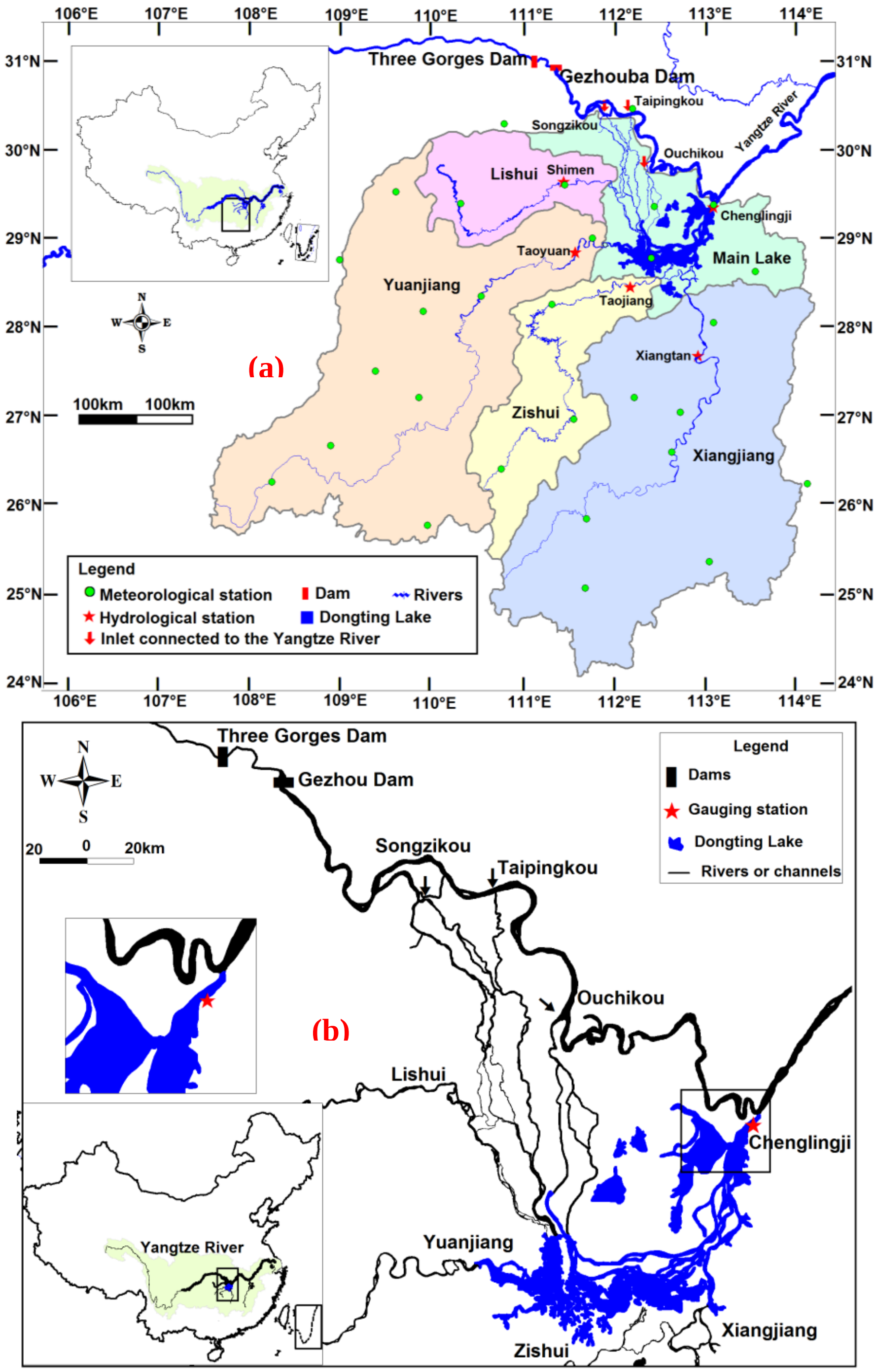


Fig. 3.1 Study area of Dongting Lake basin, and the location of hydrological and meteorological stations (a), as well as the enlarged locations of the two biggest dams, TGD (Three Gorges Dam) and GD (Gezhou Dam) (b)

Dongting Lake is one of the most important hydrologic networks of the Yangtze River Basin because of its large water surface area, volume and great water contribution to the basin. It not only serves as an important natural reservoir for the upstream rivers, but also provides a valuable habitat for abundant birds, fish and vegetation. Listed as a Ramsar wetland of international importance, the lake is a vast complex of large shallow freshwater lakes, numerous small lakes, extensive freshwater marshes and swamps, and wet grassy plains with a network of interconnecting river channels, streams and canals. In addition, the area serves other significant functions, including flood mitigation, water supply and wastewater treatment, and transportation.

3.2 Data sources

For the four sub-basins, Xiangjiang, Zishui, Yuanjiang, Lishui, and the whole Dongting Lake basin, the five hydrological stations, namely, Xiangtan, Taojiang, Taoyuan, Shimen and Chenglingji hydrological stations are the five corresponding controlling gauging stations (red stars in Fig. 3.1(a)), which are all located above the interception of each study region and thus can capture the flow originating from upstream study regions. As for the three distributary channels (Songzikou, Taipingkou, Ouchikou), which connect the Yangtze River with Dongting Lake, another five gauging stations are the controlling stations. Songzikou is controlled by Xinjiangkou station in the west and Shadaoguan station in the east, Taipingkou is controlled by Mituosi station, and Ouchikou is controlled by Kangjiagang in the west and Guanjiapu in the east. Observed daily discharge over the ten gauging stations is collected from Changjiang Water Resource Commission (CWRC). The data fully cover from 1 January

1960 to 31 December 2014 and are quality controlled by the office of the Hydrological Bureau of CWRC in Wuhan, China. The daily discharge over each gauging station can be converted to monthly and annual mean discharge and flow volume. Accordingly, the annual flow volume can be converted to annual runoff depth over each study region using the respective area of the study region.

Meanwhile, meteorological data including daily precipitation, maximum, minimum and average air temperature, relative humidity, sunshine hours, actual vapour pressure, and wind speed over 29 fairly evenly distributed meteorological gauging stations (green points in Fig. 3.1) are available from the National Climatic Centre of the China Meteorological Administration (CMA). To guarantee the data consistency and integrity, the length of the data used in this study runs from 1 January 1960 to 31 December 2014. The meteorological data in most stations are continuously measured and all the data are quality controlled before releasing. The missing data are interpolated based upon available data from the adjacent gauging stations during the same periods. Over each station, the annual meteorological data are calculated based on the observed daily data. Based on the annual meteorological data, the annual potential evapotranspiration is calculated using the FAO-Penman-Monteith equation recommended by the Food and Agricultural Organization (Allen et al., 1998). To compute the regional annual precipitation, temperature and potential evapotranspiration, the Thiessen Polygons interpolation method is used to spatially interpolate the annual precipitation, temperature and potential evapotranspiration over the 29 gauging stations during the period of 1960-2014. The annual actual evaporation over each study region is the difference between regional annual precipitation and regional annual runoff depth by assuming zero storage change.

3.3 Climate and hydrology

Donting Lake basin is located in the subtropical monsoon climatic region with an annual mean precipitation of 1400mm and an annual mean temperature of 16.8℃. Precipitation in the basin exhibits remarkable inter-annual variation with a range of 995-1890mm, thus causing frequent flood and drought disasters. Affected by the alteration of East Asian winter monsoon and summer monsoon, precipitation shows seasonal distribution with over 50% of the total annual precipitation occurring from April to August (Fig. 3.2(a)). Precipitation over all the five study regions are almost synchronously distributed within the year, while the maximum monthly precipitation over Lishui sub-basin lags one month behind that over Xiangjiang sub-basin. During the wet period from March to October, streamflow generated from the heavy precipitation over all the four sub-basins drains into the Main Lake area, leading to high discharge over the lake outlet of Chenglingji [Fig. 3.2(a) and (b)] Although both the four river tributaries and the three channels contribute to streamflow during the wet period, their runoff rhythm is not synchronous. The four river tributaries are the dominant inflow sources for the lake area before June, after which the four river tributaries and the three channels play almost equivalent roles in supplying water for lake area. The peak discharge over the four tributaries occurs in June, which is one month ahead of that over the three channels. During the dry period from October to the next February, streamflow from the four tributaries is the crucial inflow for the lake area, whilst streamflow over the three channels is extreme low.

In response to the precipitation and inflow from the four river tributaries and the three channels, the lake area has seasonal fluctuation in water level, with a maximum difference of 18 meters between the flooding season and the dry season. It has a large inundation area in the flooding season from June to late August, while it turns into various small lakes, vast marshes and swamps in the dry season. In the flood season, the water surface area is normally above 2500 km^2 because of the vast volumes of flow from the Yangtze River and the four tributary rivers, while it may decrease to less than 500 km^2 in the dry season (Wu and Liu, 2016). These unique wetland conditions provide abundant nutrients and perfect habitats for a diverse range of plants, birds, fish, frogs, reptiles and mammals. As such, the Main Lake sub-basin has been designated as Ramsar wetland of international importance.

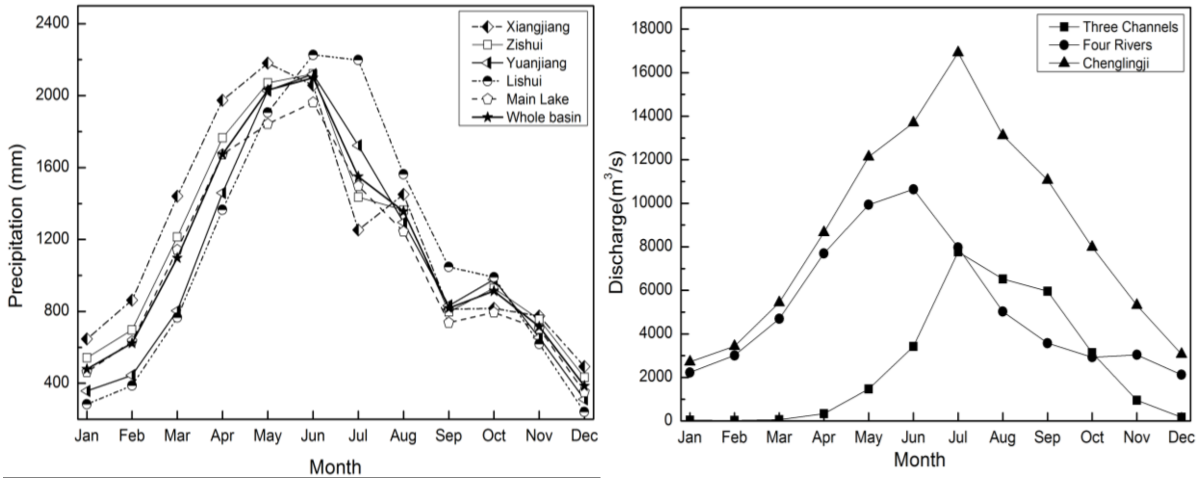


Fig. 3.2 Mean monthly precipitation over the five sub-basins and the whole Dongting Lake basin (a) and discharge for the four river tributaries, three channels and lake outlet, Chenglingji (b) during the period 1960-2014

3.4 Land use/cover and human activities

From 1980-2000, the areas of three land use types (farmland, woodland and unused land) decreased to various extents in Dongting Lake basin, while areas of other three land use types (water area, grassland and built-up area) increased during the same period. As shown in Table 3-1 (Li et al., 2004), cultivated land decreased by over 300 km^2 in 1980-2000, occupying 1.97% of the total cultivated land. It should be noted that unused land including beaches and swamp, which were easily affected by the seasonal fluctuation of water level, decreased significantly during the two decades from 1980 to 2000. It shrank remarkably by 69.39% in the first decade, while expanded slightly by 0.27% in the second decade. By contrast, the area of built-up land increased dramatically by 14.88% during the two decades, with an increase of 7.70% in the first decade and a further increase of 7.18% in the second decade. From 1980 to 1990, farmland, water body, built-up land and unused land experienced the most obvious changes, with corresponding decreases of 1.39% and 69.66% in farmland and unused land, and corresponding increases of 8.48% and 7.70% in water body and built-up land. From 1990 to 2000, changes of land use/ cover were mainly in farmland, grassland, water bodies and built-up land, with a decrease of 0.57% in cultivated land area, corresponding increases of 2.33% and 0.31% in grassland and water bodies, and an increase of 7.18% in built-up land (Li et al., 2003, Li et al., 2004). It is firmly related to the economic conditions with rapid land use changes in Shishou, Yueyang and Jinshi cities which experienced the economic prosperity of the region.

Table 3-1 The net area changes of the land use/cover in Dongting Lake basin during different periods. (Li et al., 2004)

Class	1980-2000		1980-1990		1990-2000	
	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)
Farmland	-306.08	-1.97	-216.16	-1.39	-89.93	-0.57
Woodland	-22.63	-0.39	-13.57	-0.23	-9.06	-0.16
Grassland	4.25	1.55	-2.18	-0.79	6.43	2.33
Water body	489.78	8.79	473.92	8.48	15.86	0.31
Built-up land	154.67	14.88	80.05	7.70	74.62	7.18
Unused land	-319.99	-69.39	-322.07	-69.66	2.08	0.27

According to the filed surveys (Deng et al., 2014), the main wetland cover is constituted by salix matsudana, populus euramevicanacv, miscanthus sacchariflorus, phragmitas communis, carex brevicuspis, phalaris arundinacea, artemisia selengensis and polygonum hydropier. And the main lake cover types are classified as wood, reed, meadow, mudflat, lake grass, and water body in consideration of the dominant species of beach vegetation and the characteristics of the remote sensing data. As shown in Table 3-2, wood and meadow increased from 1993 to 2010, and other types of land cover decreased. Reed increased considerably from 1993 to 2006, while decreased significantly thereafter, with a slight overall decrease from 760.75 km^2 in 1993 to 717.67 km^2 in 2010. Meadow expanded rapidly from 1993 to 2002, while shrank sharply from 2002 to 2006, followed by a prominent recover in 2010. The total area of mudflat, lake grass and water body remarkably reduced by 334.07 km^2 from 1993 to 2010, especially during the period of 1993-2002.

Table 3-2 Percentages of land cover types in Dongting Lake during different periods (%) (Deng et al., 2014)

Cover type	1993	2002	2006	2010
Wood	1.17	5.04	13.09	14.34
Reed	27.26	27.76	28.66	25.66
Meadow	26.95	31.96	21.65	27.03
Mudflat	16.61	12.92	6.31	9.38
Lake grass	0.55	2.09	2.94	2.58
Water body	27.46	20.03	27.38	21.02

Dongting Lake basin, heavily populated, is one of China's leading regions producing rice, cotton and fish. The rich sediment of the marshland attracted farmers to build embankments to separate the Yangtze River and thus gain more farmland. According to the record, of the

1,830 km^2 of cultivated land reclaimed from the main lake during the period of 1949-1979, about half was reclaimed from the inner lake body (Li et al., 2003). There was 0.34 million ha of farmland area surrounded by 228 embankments until 1998 (Li et al., 2007). Until recently, the main Dongting Lake region consists of 3740 km long main flood embankment, 218 polders, 3 natural lakes (West, South and East Dongting Lake) and 8 flood water channels connecting these lakes (Li et al., 2009). This led to increasingly shrank lake area and storage capacity resulted from the increasing mud and sand silt. According to the historical record, during the period of 1956-1998, average silt discharge into the lake was 1.29×10^8 t/a from the three channels, while only 0.298×10^8 t/a was derived from its own drainage basin through the Four Rivers (Yin et al., 2007). In the past 8 decades, Dongting Lake underwent significant degradation with an average decrease rate of 38.1 km^2/yr in the water surface area (Zhao et al., 2004). The lake was also fragmented with decreases in patch sizes but increases in patch numbers. The degradation of the lake resulted largely from extensive impoldering and long-term siltation (Zhao et al., 2004, Jiang et al., 2007). The impoldering from the lowland has directly led to a rapid diminished lake area and storage capacity and caused the increasing deterioration of the flood diversion and flood storage capacity, which posed severe flood disaster threaten to the residents in the region.

After a disastrous flood event in 1998, which caused 3,656 deaths, 378,000 people homeless and a loss of US $737 million (Ding and Li, 2011), the government of China began to launch the Return Land to Lake Program for flood control. The program planned to return cultivated land into lake area and remove embankments and relocate residents living inside diked lands to other place to eventually increase the lake area by about 779 km^2 in the following five years (Ding and Li, 2011). Since the 1990s, the booming economic growth in the region was accompanied with overexploitation of lake resources. From 2000 to 2008, the total lake area decreased significantly because of accumulated sedimentation in the lake, vegetation succession on lakeside zone, and human activities (e.g. upstream dam construction, construction of lakeside tourist facility, and lakeshore industry development). However, the decreasing trend in lake area in 2000-2008 slowed down compared with that in the period of 1990 to 2000, which might be attributed to the Return Land to Lake Program as well as the implementation of wetland conservation and restoration projects (Cui et al., 2013).

Among all the anthropogenic activities, upstream dam regulation is considered by many researchers to be the most dominant factor that alters flow regimes in Dongting Lake. In the past several decades, the upper reaches of the Yangtze River have been extensively dammed, with a total reservoir capacity of over 100 $\times 10^9$ m^3 (http://www.moc.gov.cn/). Among all the dams, TGD and GD are the two biggest dams which attract global attention (Fig. 3.1). In 1981, GD, the first largest dam in the Yangtze River Basin, went into operation with a storage capacity of 1.58 $\times 10^9$ m^3. 23 years after GD, located 38 km upstream from GD and 400 km upstream of Dongting Lake's outlet (Chenglingji), TGD started impounding in June 2003. With a normal pool level of 175 m and a total reservoir storage capacity of 39.3 $\times 10^9$ m^3, it is the largest water conservancy project ever undertaken in China, and indeed in the world. The operation of TGD can be divided into four modes, namely, water-supplement mode (releasing water for downstream water supplement from January to March), pre-discharge mode (releasing water for downstream flood control preparation from 25 May to 10 June), flood-control mode (adjusting water for downstream flood control from 1 July to 31 August), and water-storage mode (impounding water for power generation and water supplement from 15 September to 31 October) (Ou et al., 2012). The dam experienced several stages to finally achieve the four operational modes, with maximum water level reaching to 139m in 2003, 156m in 2006, 170m in 2008 and 175m in 2010. The two giant dams benefit flood control, power generation, irrigation and navigation. However, by reallocating water resources for different operational purposes, the downstream natural flow and sediment transport, surficial geology, water balance and ecological connectivity have been profoundly affected by the dams (Dai et al., 2008, Feng et al., 2013, Ou et al., 2014, Wu et al., 2015a). As a complex dynamic lake, the natural hydrologic regimes in Dongting Lake are vulnerable to the dam regulations.

3.5 Conclusions

Dongting Lake is the second largest freshwater lake in China, which is fed by the Yangtze River via Three Channels in the north, and Four Rivers in the south. Water from these inlets finally flows into the Yangtze River through its single outlet, Chenglingji, resulting in a complicated river-lake relation. Observed daily discharge over 10 hydrological gauging stations, and meteorological data including daily precipitation, air temperature, relative humidity, sunshine hours, actual vapour pressure, and wind speed over 29 fairly evenly distributed meteorological gauging stations, spanning from 1960 to 2014 are collected and processed for further analysis.

Affected by subtropical monsoon climate, both precipitation and streamflow exhibits remarkable seasonal variations. Over half of the annual precipitation occurs during the flood season from April to August, corresponding to high discharge during the same period. The runoff rhythms of Three Channels and Four Rivers are not synchronous. Four Rivers serve as the dominant inflow sources for the lake before June, while hereafter Three Channels and Four Rivers play almost equivalent roles in supplying water for lake area.

Land use/cover types over Dongting Lake area can be mainly divided into five types, namely, farmland, woodland, grassland, water body, built-up land, unused land according to the land use purpose. Meanwhile, the main lake cover types can be classified as wood, reed, meadow, mudflat, lake grass, and water body in terms of the dominant species of beach vegetation and the characteristics of the remote sensing data. No matter how the land use/cover types are classified, they are significantly affected by the regional economic development. The lake suffered from extensive impoldering and long-term siltation in the past several decades, which caused severe degradation of the lake. Besides, upstream human activities, especially the regulation of TGD and GD, may largely affect the natural hydrologic regimes in Dongting Lake through changing the river-lake relation between the Yangtze River and Dongting Lake.

4 VARIATIONS OF FLOW REGIEME IN DONGTING LAKE

4.1 Introduction

Natural hydrologic patterns of rivers are vulnerable to both human activities and climate change and variability. Dongting Lake, as the second largest lake regulating runoff and sediment from the Yangtze River, is inevitably affected by the upstream dam regulations and changing climate. It is, however, difficult to differentiate how much of streamflow is changed by human activities and climate impact, respectively. As one of the world’s largest hydropower projects, Three Gorges Dam (TGD, see Fig. 4.1) has attracted widespread criticism and concern about the impacts on downstream hydrological regimes. Therefore, this chapter first aims to identify the observed flow regime changes in Dongting Lake after the operation of TGD, and to relate the degrees of hydrologic alteration to the modes of dam operation, based on observed daily water level and discharge data over Chenglingji gauging station spanning from 1960 to 2014.

To further quantify the detailed hydrologic alterations of Dongting Lake, the whole study period of 1960-2014 is divided into three sub-periods according to the beginning of upstream dam regulations of Gezhou Dam (GD) and TGD, which are the two biggest Chinese dams (Fig. 4.1). Then, a set of hydrologic metrics is used to investigate the pre- and post-dam hydrologic changes in flow magnitude, frequency, duration, timing and rate of change at the annual, quarterly, monthly, weekly and daily scales. This can systematically characterize the natural flow regimes before dam impacts, and comprehensively examine the prevailing hydrologic alterations in Dongting Lake, China, following the two upstream dam regulations.

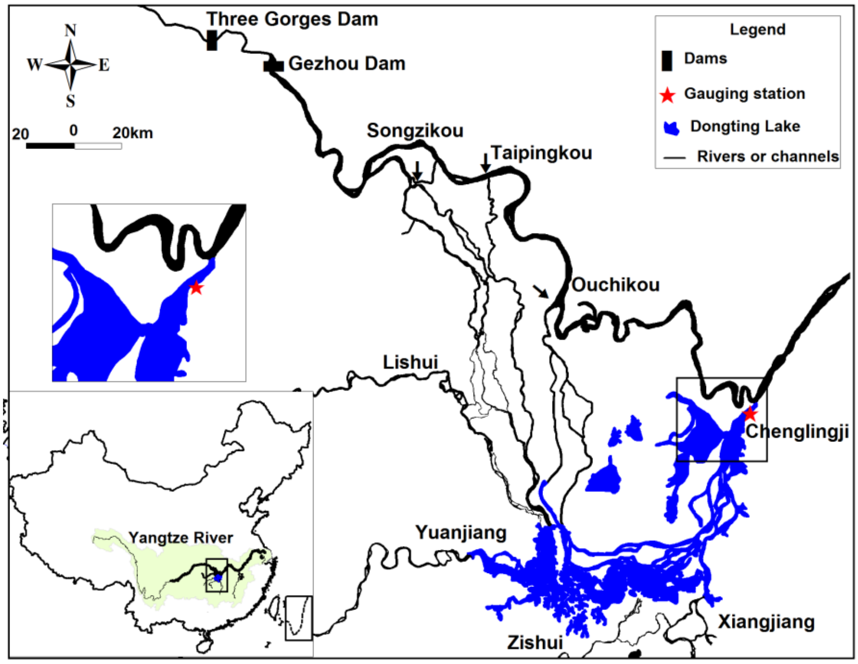


Fig. 4.1 Study area of Dongting Lake basin, and the location of hydrological stations and the two biggest dams, TGD (Three Gorges Dam) and GD (Gezhou Dam)

4.2 Flow regime changes after TGD

4.2.1 Introduction

The regulation of TGD has altered the natural flow regime downstream by reallocating river water under different operational modes. To understand the hydrologic alteration in Dongting Lake, daily time series of water level and discharge from 1960 to 2014 data at 6 gauging stations are collected. Except Chenglingji station, the other 5 stations are located in the three channels connecting the river with the lake. Xinjiangkou and Shadaoguan stations are at Songzikou, Mituosi station is at Taipingkou, and Kangjiagang and Guanjiapu stations are at Ouchikou (Fig. 3.1). Daily water level before TGD site, and discharge before and after the dam site from 2003 to 2014 are also collected. To investigate the changes of water quantity from the Yangtze River to the lake, annual total flow at the 5 gauging stations before and after the dam regulation is compared. Alteration of discharge and water level at the outlet (Chenglingji) of the lake are also analysed at a seasonal scale. To further examine lake flow alteration associated with dam regulation, daily flow duration curves for Chenglingji gauging station under four operational modes during pre- and post-dam periods are plotted and analysed based on the frequency of daily flow discharge in different ranges. By comparing the difference of flow duration curves, changing relationships between magnitude and frequency of daily discharge can be identified. Also, water level-discharge rating curves for Chenglingji station are established to explore changes in the relationship between lake water level and discharge.

4.2.2 Variations of inflow from the Yangtze River

Following the impoundment of TGD in 2003, there have been strong changes to the quantity of water from the Yangtze River to Dongting Lake. Since 2003, annual flow from the river to the lake through all three channels Songzikou, Taipingkou and Ouchikou has reduced dramatically, as shown in Table 4 1. Annual mean total inflow from the river has decreased by almost 50%, from around 94.17 ×109 m^3 before 2003 to 49.07 ×109 m^3 after 2003. The inflow mainly comes from east Songzikou and east Ouchikou, with an annual mean discharge of about 31 ×109 m^3 from each branch before 2003, accounting for 67% of total inflow from the river. However, both branches have experienced remarkable reduction since 2003, especially for east Ouchikou, whose annual mean discharge has reduced by 67%. Inflow from west Songzikou and Taipingkou has also seen a decrease of nearly 50%, decreasing from 11.35 ×109 m^3 and 16.81 ×109 m^3 to 5.35 ×109 m^3 and 9.01 ×109 m^3, respectively. Although water from west Ouchikou accounts for only a small portion of the total inflow, it has exhibited the most notable change with a reduction of 86% in annual mean discharge during post-dam period.

It can be referred from the table that even the maximum annual inflow (65.42 ×109 m^3 in 2012) after dam regulation is far less than the annual mean inflow before dam regulation. This situation is greatly exacerbated in a dry year. In 2006, when extreme drought happened in the whole Yangtze River basin, the total inflow from the river fell to merely 18.26 ×109 m^3, no more than 20% of the annual mean water before 2003. It seems the historical water balance relationship has been changed, and a new relationship has been established. For all these channels connecting the river with the lake, inflow from the river was maintained in a basically stable state during post-dam period except in extreme water situations. For example, flow in east Songzikou stays in a range of 21~26 ×109 m^3 after 2003 except in those extreme dry or wet years 2005, 2006, 2011 and 2012.

The significant alteration of inflow from the Yangtze River to Dongting Lake might be related to the hydrologic and morphologic changes in the river caused by dam regulation. Considering the capacity of TGD and the huge area of the Yangtze River downstream of the dam, the impact of the dam on annual discharge downstream can be neglected, and it only greatly modifies the seasonal flow distribution. However, apart from altering the seasonal flow downstream, TGD has also caused riverbed erosion downstream of TGD by trapping more sediment in the reservoir. The riverbed has turned from depositional before the dam construction to erosional afterwards (Dai and Liu, 2013). The lowered riverbed increased the elevation difference between the river and the channels connecting to the lake, thus more water goes directly to the river downstream rather than flowing into the lake through the channels.

Table 4-1 Annual flow volume of Three Channels connecting the Yangtze River with Dongting Lake

Annual Q ($10^9 m^3$)	Songzikou (East)	Songzikou (West)	Taipingkou	Ouchikou (West)	Ouchikou (East)	Total
Control stations	Xinjiangkou	Shadaoguan	Mituosi	Kangjiagang	Guanjiapu	
Average	(1960-2002)	(1960-2002)	(1960-2002)	(1960-2002)	(1960-2002)	
	31.18	11.35	16.81	3.11	31.72	94.17
	(2003-2014)	(2003-2014)	(2003-2014)	(2003-2014)	(2003-2014)	(2003-2014)
	23.84	5.35	9.01	0.42	10.45	49.07
2003	25.69	6.93	10.57	0.72	12.96	56.87
2004	25.32	5.77	10.37	0.46	10.51	52.43
2005	30.08	7.62	12.28	0.71	13.65	64.33
2006	10.87	1.04	3.43	0.05	2.87	18.26
2007	25.69	6.10	9.98	0.59	12.01	54.36
2008	25.70	5.61	9.87	0.40	11.29	52.87
2009	21.50	4.85	8.67	0.33	9.74	45.09
2010	25.96	6.24	10.70	0.58	13.13	56.60
2011	15.84	2.17	4.73	0.06	4.44	27.24
2012	31.35	7.51	11.42	0.64	14.50	65.42
2013	20.62	4.10	6.94	0.17	7.95	39.78
2014	27.45	6.25	9.16	0.33	12.34	55.53

4.2.3 Variations of seasonal flow regime

Being the only outlet in the lake and connecting the river with the lake, Chenglingji plays a vital role for both Dongting Lake and the Yangtze River. Observed hydrologic data from Chenglingji gauging station (Fig. 3.1) is used to represent the hydrologic characteristics for the whole lake. Water level and discharge from Chenglingji station before and after the dam regulation is compared to investigate the seasonal flow pattern change in the lake, as shown in Fig. 4.2. It is further confirmed that discharge in the lake has significantly reduced following dam regulation. Except in February and March, discharge in the remaining ten months has become lower after dam regulation, especially in flood periods, with a maximum reduction of 6,173 m^3/s. The patterns of seasonal lake discharge changes are related to the modes of dam operation (Fig. 4.2 and Fig. 4.3). In March, lake discharge is slightly higher (216 m^3/s higher), corresponding to water releasing from TGD under the water supplement mode. The increased lake discharge is beneficial to spring drought relief in the lake area. From late May to early June, decreased lake discharge after dam regulation is corresponding to modified discharge by TGD under pre-discharge mode. In the flood period from July to August, lake discharge reduces remarkably (a maximum reduction of 6,173 m^3/s) when TGD adjusts the downstream flow by storing more water in the reservoir under flood-control mode, which helps to alleviate summer flood in the lake area. Also, less water into the lake means less sediment, which makes the sedimentation problem in the lake less severe. Although TGD contributes to drought relief and sediment management in flood periods, it exacerbates the lake's drought in dry periods. In the dry period from September to October, TGD impounds water under water-storage mode, thus lake discharge decreases with less water drained downstream from TGD. The reduced lake discharge in dry period can increase the vulnerability to autumn drought in the lake area.

As can been seen from Fig. 4.2, the seasonal change of water level in Dongting Lake can also be affected by the operational modes of TGD, whose regulated discharge has negative impact on lake water level. Although lake water level shows a similar changing trend with discharge within the year, the changing magnitudes are largely different. Lake water level becomes lower only under flood-control and water-storage modes, with a maximum difference of 1.85 m in October. Under water supplement and pre-discharge modes, water level is higher than that without dam regulation, with a maximum difference of 1.5 m in March. From December to the next April, when lake discharge is still lower after dam regulation (except in March), water level is maintained at a higher level, which may be due to the stronger blocking effect of the Yangtze River (Wang et al., 2013a).

Notably, flow regime in the lake has changed at seasonal scale, and is closely related to regulatory influence of TGD. By adjusting dam outflow under different modes, the natural seasonality of lake discharge and water level has been altered to varying degrees, which can be reflected by the disruption of normal reducing or increasing flow, modified frequency, duration, magnitude and timing of flow events. Therefore, it is necessary to examine the flow regime alteration under different operational modes of TGD.

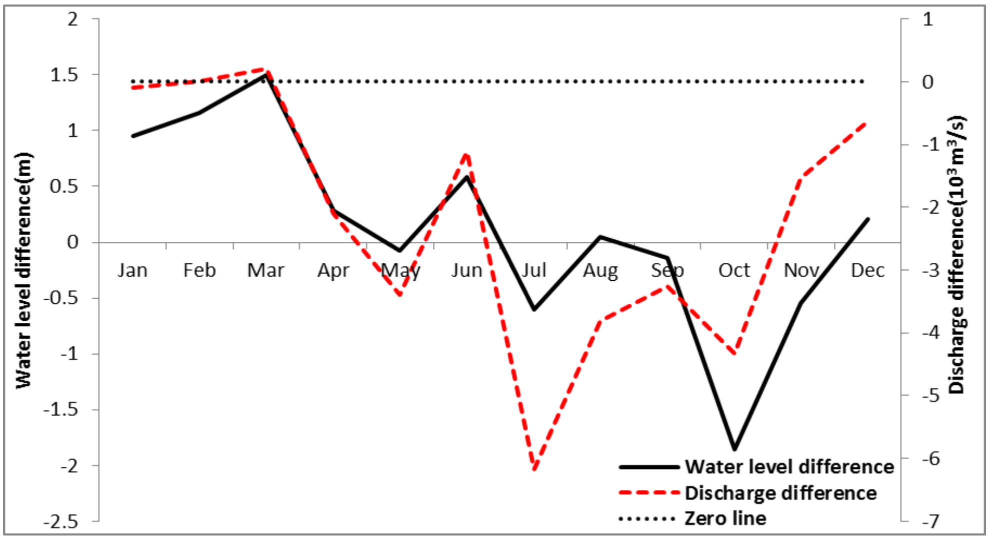


Fig. 4.2 Discharge and water level differences at Chenglingji gauging station between post-dam (2003-2014) and pre-dam (1960-2002). Dotted zero line indicates the zero level for discharge difference

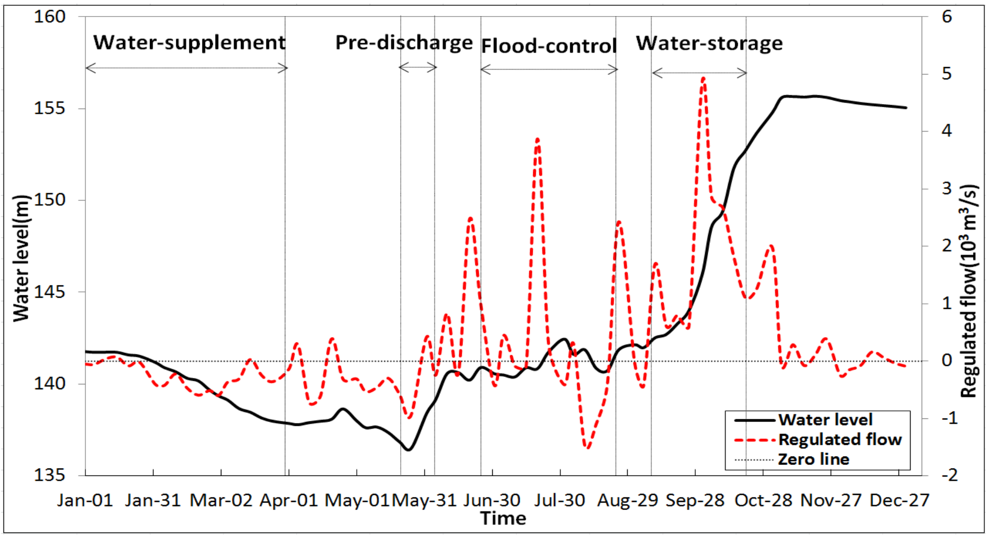


Fig. 4.3 Daily mean water level before the dam site and regulated flow for 2003-2014. Positive value for water impounding and negative for releasing. Dotted zero line indicates the zero level for regulated flow

4.2.4 Variations of flow regime under four dam operational modes

Hydrologic changes associated with dam regulation can be reflected in the shape and characteristics of flow duration curve, which is a useful indicator of temporal variability in the record (Magilligan and Nislow, 2005). A flow-duration curve is a cumulative frequency curve that shows the percentage of time specified flows are equalled or exceeded for a given period of time. The slope of the curve indicates the variability or flashiness of discharge for a period of time. To further investigate the influence of the dam regulation on flow duration statistics, daily flow duration curves under different operational modes for pre- and post-dam periods were computed and plotted based on daily discharge from Chenglingji gauging station (Fig. 4.4). The four dam operational modes are water-supplement mode (releasing water for downstream water supplement from January to March), pre-discharge mode (releasing water for downstream flood control preparation from 25 May to 10 June), flood-control mode (adjusting water for downstream flood control from 1 July to 31 August), and water-storage mode (impounding water for power generation and water supplement from 15 September to 31 October) (Ou et al., 2012).

As noted in Fig. 4.4 that curve shapes under all operational modes have been changed considerably after dam regulation. Except for water-supplement mode, comparisons of duration curves between pre- and post-dam periods show a slight downward shift and a flat shape for all the other three operational modes, further confirming an overall decrease in discharge after dam regulation. The downward shift is most prominent under flood-control mode and water-storage mode, followed by pre-discharge mode, which reveals that the dominant impact of TGD occurs in flood and dry periods. Flow has become flashy (rises and recedes more rapidly), and high flow magnitude is remarkably lowered during the post-dam period than that in the pre-dam period for all four modes. Specifically, the maximum daily flow has dropped by 36.3%, 41.4%, 45.1% and 62.8% under water-supplement mode, pre-discharge mode, flood-control mode and water-storage mode, respectively. Within the 5 percentile range, the curves flatten out considerably, notably for pre-discharge mode, flood-control mode and water-storage mode. The decreased high flow magnitudes and flattened slopes reflect discharge within the 5 percentile fluctuates stably within a smaller range. The alteration of high flow in flood period benefits flood control and sediment management in the lake area. However, the lack of high flow may pose potential negative impact on lake wetlands, significantly disrupting ecological integrity. In additional to decreased high flow magnitude, a slight decrease in low flow magnitude can also be found under all operational modes except for pre-discharge mode, this finding is the same as other researchers (Lai et al., 2012, Hu et al., 2015b). The reduced low flow magnitude, especially in dry seasons, may induce water shortage problems and exert a considerable influence on lake wetlands (Lai et al., 2013, Xie et al., 2015). This problem also occurs in Poyang Lake, which is the first largest freshwater lake in China and whose wetlands have been affected significantly by the decreased lake water levels (Mei et al., 2015, Feng et al., 2016). Compared to those during the pre-dam period, flow duration curves after dam regulation have become flashier under all four operational modes. The flashiness is extremely obvious when TGD adjusts outflow from the reservoir to prepare for flood control under pre-discharge mode. There is a break in the duration curve slope near the 50% exceedance level, and discharge changes rapidly from 7960 m^3/s to 5050 m^3/s between the 85 and 90 percentile ranges.

As lake discharge has increased under water-supplement mode (Fig. 4.2), the flow duration curve exhibits a slight upward shift above 7 percentile. The curve slope for high magnitude flow is steeper after dam regulation, indicating that high magnitude discharge is infrequent and not sustained for long periods of time. The comparison indicates that the duration of flow greater than 8550 m^3/s is shorter in the post-dam period, whilst the duration of discharge smaller than 8550 m^3/s is longer in the post-dam period. Specifically, flow between the 20 and 40 flow duration percentiles has increased by 150~1000 m^3/s since dam construction. Although discharge remains elevated above 45 percentile, the increase is not obvious.

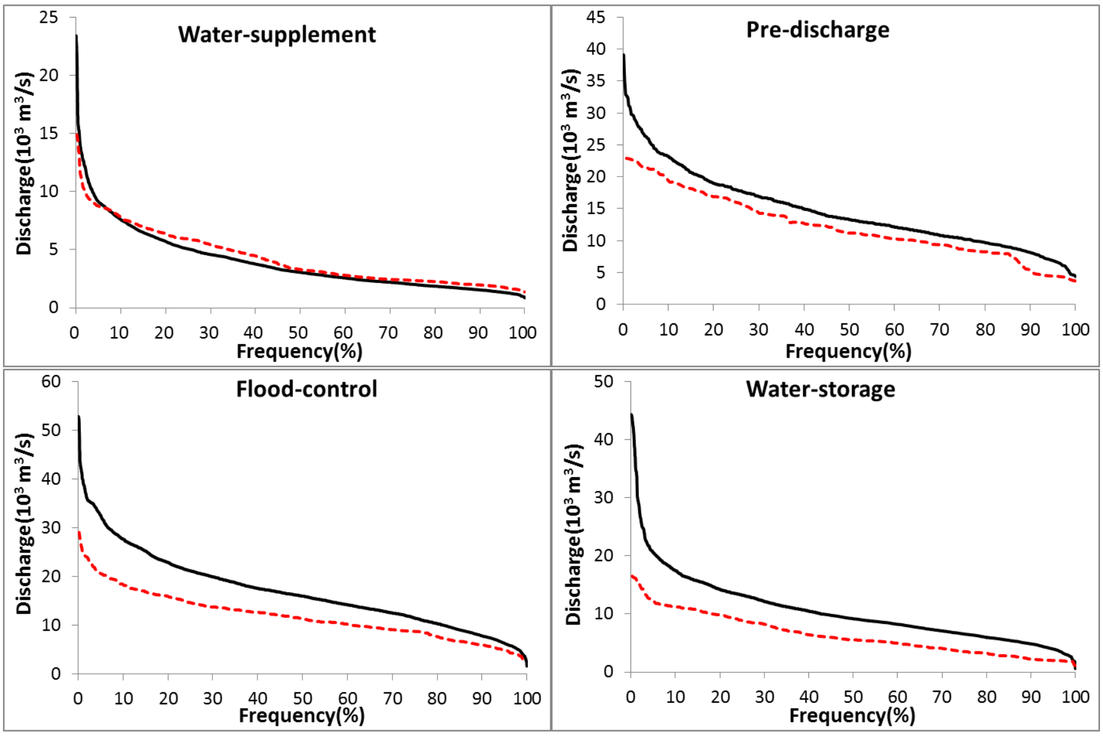


Fig. 4.4 Pre- and post-dam flow duration curves for 4 operational modes of TGD (Black solid curves for pre-dam and red dotted curves for post-dam)

Apart from flow duration curves, water level-discharge rating curves also provide a simple but comprehensive graphical view of lake flow variability through the relationship between water level and discharge. Flow regime alteration can be detected from the changing shape of rating curves. Water level-discharge rating curves are established under dam operational modes before and after dam regulation by plotting the measured discharges from Chenglingji gauging station against the corresponding stages and drawing a smooth curve of the relation between the two quantities, as shown in Fig. 4.5. The rating curves indicate that the relationship between water level and discharge has experienced notable variation with a substantial downward shift under all four modes from pre-dam period to post-dam period. The downward shift indicates a reduction in discharge corresponding to the same water level, which might be due to the blocking effect of the Yangtze River. All rating curves during the post-dam period also exhibit a moderate fluctuation in both discharge and water level with a decrease in high magnitude discharge and water level, as well as an increase in low magnitude water level. Although low magnitude water level is elevated under all modes after dam regulation, the corresponding low magnitude discharge remains low, with reduced discharge under pre-discharge mode and water-storage mode compared to that before dam regulation. This phenomenon might be attributed to the blocking effect of the Yangtze River (Wang et al., 2013a).

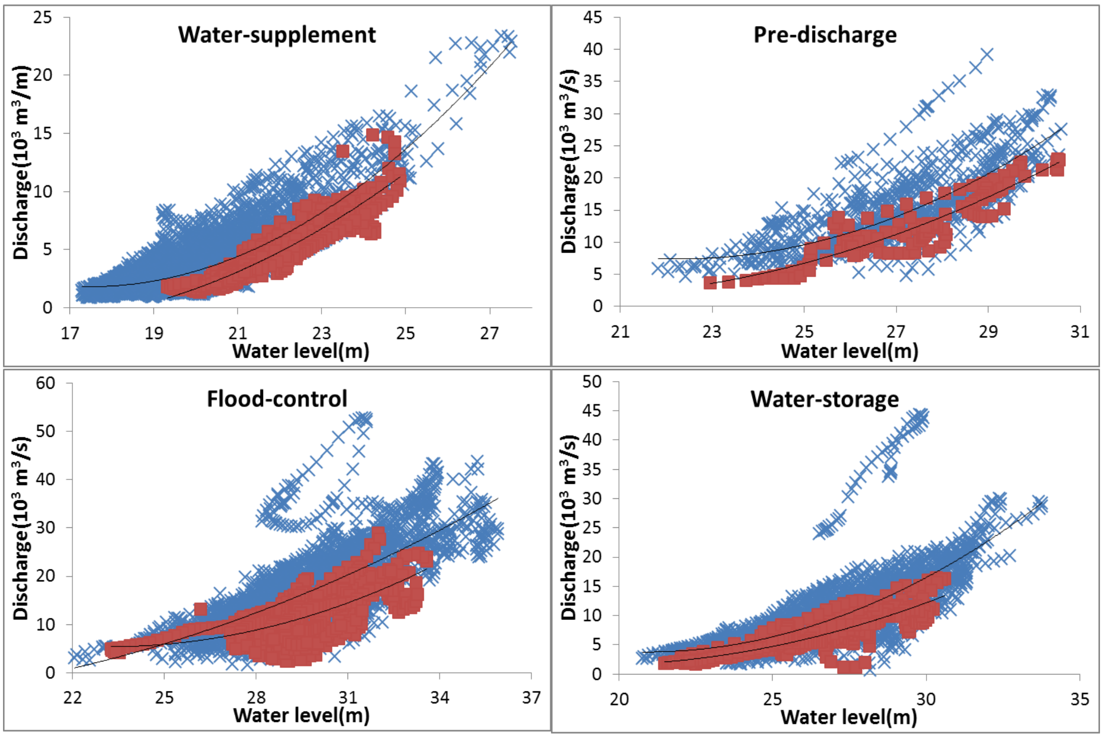


Fig. 4.5 Pre- and post-dam rating curves for 4 operational modes of TGD (Blue cross scatters for pre-dam and red square scatters for post-dam, black solid lines are the fitting lines)

4.2.5 Discussion

Comparisons of the previous or current flow regime conditions with natural flow regime can cast light on the degree of departure from natural flow conditions that has already occurred. It can provide important reference to flow protection and restoration activities, sustainable ecological research and monitoring, and priority management actions. The above study provides an improved understanding of hydrologic alteration in Dongting Lake following TGD regulation, and such understanding is essential for the lake and wetland management. As flow regime controls many physical and ecological aspects of lake form and processes, the alteration of natural flow regime in Dongting Lake could have a variety of impacts on lake wetlands and ecosystem. By changing the magnitude, frequency, timing and duration of flow, available habitat could be reduced (Lai et al., 2013, Deng et al., 2014). With the reduction of lake discharge and water level following dam regulation, the extent and frequency of flooding of terminal wetlands could be reduced, especially during dry period. Thus, the natural biological diversity and ecological function would be disrupted (Zhang et al., 2014b, Wu et al., 2015b). Also, altered flow pattern could affect natural processes of sediment erosion, transport and deposition, causing bank erosion and sediment transport problem(Ou et al., 2011, Zhou et al., 2015).

This section restricts its exploration to the flow regime alteration in Dongting Lake and potential effects of the operational modes by TGD. Several limitations of exist, however, especially in lack of precipitation and inflow data from the four rivers (Lishui, Yuanjiang, Zishui and Xiangjiang), which might imply compromised effects of TGD on flow regime alteration in Dongting Lake. Also, the length of time series data after dam construction is far less than that before dam construction, which might exaggerate dam effect. Although we recognise the importance of the above factors for flow regime, we limit this study to measurable hydrologic alteration from the gauging records.

4.3 Flow regime changes following the GD and TGD

4.3.1 Introduction

The above section has revealed that flow regimes in Dongting Lake have been potentially changed by the operation of TGD under different operational modes. However, it is mainly focused on illustrating the changes of inflow from the Yangzte River to the lake, the shapes of flow duration curves and the relationships between water level and discharge. Besides, the study simply compared the flow conditions before and after the impoundment of TGD regardless of the potential regulation impact of GD. The study does not delineate the full range of the flow regime, which is characterized by five critical hydrologic components (magnitude, frequency, duration, timing, and changing rate of hydrologic conditions). It is clear, however, that the full range of hydrologic regime is essential for describing the overall flow characteristics and specific hydrologic phenomena like floods and droughts, as well as the ecological consequences modified by human activities (Poff et al., 1997, Richter et al., 1997). Moreover, water resources management and ecosystem protection requires adequate hydrologic metrics in describing the flow variation, magnitude, timing, frequency, duration, and rates of change of the flow regimes. This is especially true for Dongting Lake wetland system, whose native biodiversity and integrity of aquatic ecosystem is sensitively affected by any of the aforementioned hydrologic metrics.

The aim of this section is to systematically characterize the natural flow regimes before dam impacts, and comprehensively examine the prevailing hydrologic alterations in Dongting Lake, China, following the two upstream dam regulations. The observed long-term daily hydrologic data spanning from 1960 to 2014 are available for the flow regime analysis before and after the dam impoundments. According to the starting time of dam regulations, the 55-year study period is divided into three sub-periods, pre-dam period, post-GD period and post-

TGD. The natural flow regimes and hydrologic shifts in the pattern, magnitude, timing, duration and direction of lake flow are investigated at the annual, quarterly, monthly, weekly and daily scales, based on the hydrologic metrics of indicators of hydrologic alteration (IHA). It is informative to understand the nature of hydrologic features in Dongting Lake and the extents to which hydrologic conditions have been affected following dam regulations. Such information is significant in investigating the causes of flow regime changes and ecological impairment, which is the basis of catchment water resources protection and management. Moreover, it provides a good example for comprehensively assessing flow regime changes in other catchments, especially where the natural hydrologic processes are heavily altered and the ecological processes are vulnerable to the hydrologic alterations.

4.3.2 Methodology

The Indicator of Hydrologic Alteration (IHA) software is developed by The Nature Conservancy (2009) to understand the characteristics of natural and altered hydrologic regimes in rivers, lakes and groundwater basins by summarizing long periods of dally hydrologic data into series of ecological relevant hydrologic parameters. The software automatically fills the gap by performing a linear interpolation across the missing data gap. If there exists a particular year without data values, this entire year will be excluded from analysis. A warning message will be issued if there is a consecutive missing data block greater than a user-defined length adequately capture annual and inter-annual variations in the flow regime. The user can choose whether to compare two distinct time periods or analyse trends over a single time periods. If a study area has experienced an abrupt change such as dam construction, the IHA can be used to analyse how the flow regime is changed by computing a suite of hydrologic parameters for the periods of before and after the impact. If the study area has suffered from accumulative human modifications, the IHA can evaluate the changing trend by computing and graph linear regressions.

Based on the daily hydrologic data, the IHA software can calculate 33 IHA parameters. The 33 IHA parameters characterize the intra and inter-annual variability in water conditions, including the magnitude, frequency, duration, timing and rate of change of flows, which has been evaluated to be an idea suite of parameters to statistically describe the full range of flow characteristics (Olden and Poff, 2003). As shown in Table 4-2, the IHA indices consist of 33 inter- and intra- annual flow metrics that fall into five major categories: (1) magnitude of monthly flow conditions (one parameter for each month); (2) magnitude and duration of annual extreme flow conditions (1-, 3-, 7-, 30-, 90-day minima and maxima, number of zero-flow days, and base flow index); (3) timing of annual extreme flow conditions (Julian date of each 1-day minimum and maximum); (4) frequency and duration of high and low pulses (number and duration of low and high pulses); and (5) rate and frequency of flow changes (rise or fall rates, and the number of hydrologic reversals). Among them, base flow index is defined as the 7-day minimum flow divided by mean flow for the year. Hydrologic pulses are defined as those periods within the year that river discharges fall below or rise above a defined lower and upper threshold. Typically, the lower threshold is defined as 25% of median pre-dam flow for the non-parametric statistics or 1 standard deviation below mean pre-dam flow for parametric statistics, respectively. Likewise, the upper threshold is defined as 75% of median pre-dam flow for the non-parametric statistics or 1 standard deviation above mean pre-dam flow for parametric statistics, respectively. The rise or fall rates are defined as the positive or negative differences of water conditions between consecutive daily values. The number of reversals is the number of times that flow switches from one type of rate to another. The suite of 33 IHA parameters can be calculated using parametric (mean/standard deviation) or nonparametric (percentile) statistics. Non-parametric statistics are a better choice because of the skewed (non-normal) nature of many hydrologic datasets (a key assumption of parametric statistics is that the data are normally distributed), (The Nature Conservancy, 2009).

Table 4-2 Indicators of hydrologic alteration (IHA) metrics (The Nature Conservancy, 2009)

IHA metric	Hydrologic parameters	IHA metric	Hydrologic parameters
Magnitude of monthly water conditions	Median value for each month	Timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum
Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean Annual minima, 3-day mean Annual minima, 7-day mean Annual minima, 30-day mean	Frequency and duration of high and low pulses	Number of low pulses within each water year Median duration of low pulses (days) Number of high pulses within each water Median duration of high pulses (days)
	Annual minima, 90-day mean Annual maxima, 1-day mean Annual maxima, 3-day mean Annual maxima, 7-day mean Annual maxima, 30-day mean Annual maxima, 90-day mean Number of zero-flow days Base flow index: 7-day minimum flow/mean flow for year	Rate and frequency of water condition changes	Rise rates: median of all positive differences between consecutive daily values Fall rates: median of all negative differences between consecutive daily values Number of hydrologic reversals

These 33 hydrologic metrics can jointly characterize the natural flow condition which is relatively unharnessed, and they can also assess the hydrologic shifts associated with perturbations (such as dam operations, flow diversion, or watershed development) (Richter et al., 1996) . Originally proposed for the conservation of river ecology and restoration of flow regimes modified by human activities (Poff et al., 1997), the set of IHA metrics has become popular in comprehensively characterizing the variability in ecologically relevant hydrologic regimes and quantifying flow alterations associated with human perturbations such as dams and water diversions (Costigan and Daniels, 2012, Caruso, 2013, Al-Faraj and Scholz, 2014, Worku et al., 2014, Yang et al., 2014, Piqué et al., 2015).

To statistically characterize the temporal variability in flow regimes of Dongting Lake, the IHA software version 7.1 (Richter et al., 1996, The Nature Conservancy, 2009) is used in calculating a subset of IHA indices by rapidly processing the daily discharge data over Chenglingji gauging station. The metric, number of zero-flow days, is excluded from this study, as there is no zero-flow observed at Chenglingji gauging station. Meanwhile, the base flow index, which is not of interest in this study, is also excluded in the analysis. A non-parametric (percentile) statistical analysis is adopted because of the skewed (non-normal) nature of the hydrologic dataset (The Nature Conservancy, 2009).

Three analysis periods, namely pre-dam period, post-GD period and post-TGD, are divided according to the starting time of dam regulations. The pre-dam period from 1960 to 1980 is defined as the benchmark period which has the least human intervention, and two post-dam periods from 1981 to 2002 (post-GD) and 2003 to 2014 (post-TGD) reflecting remarkable upstream damming are compared with the benchmark period to quantify the flow alteration at various temporal scales. The flow anomaly over the two post-dam periods is defined as the difference between post- and pre-dam flow divided by pre-dam flow. To examine the significance in flow changes after dam regulations, Student's t-test, commonly used in testing for the significant differences in streamflow between the two time periods (McCabe and Wolock, 2002, Meitzen, 2016), is performed against the pre-dam period and each post-dam period.

Flow duration curves over the pre- and post-dam periods are established through calculating the percent of time that the specified flow is equalled or exceeded using the daily discharge. The hydrologic alteration associated with dam regulations can be reflected in the shape and characteristics of the flow duration curve (Magilligan and Nislow, 2005), which provides a simple but comprehensive graphical view of flow variability.

4.3.3 Natural flow characteristics

The long-term mean annual discharge during the benchmark period of 1960-1980 was 9347 m^3/s, corresponding to a total annual volume of 294.78×10^9 m^3. The natural flow exhibited high intra-annual variation during the observed pre-dam period, as illustrated in Fig. 4.6. The annual coefficient of variation (CV) of the flowrate was 0.74. The maximum annual volume of 398.64×10^9 m^3 was detected in 1964 when an extreme flood occurred over Dongting Lake area. The minimum discharge of 6307 m^3/s was found in 1978 when discharge reduced by 50% from July to October compared to the long-term mean value under natural condition.

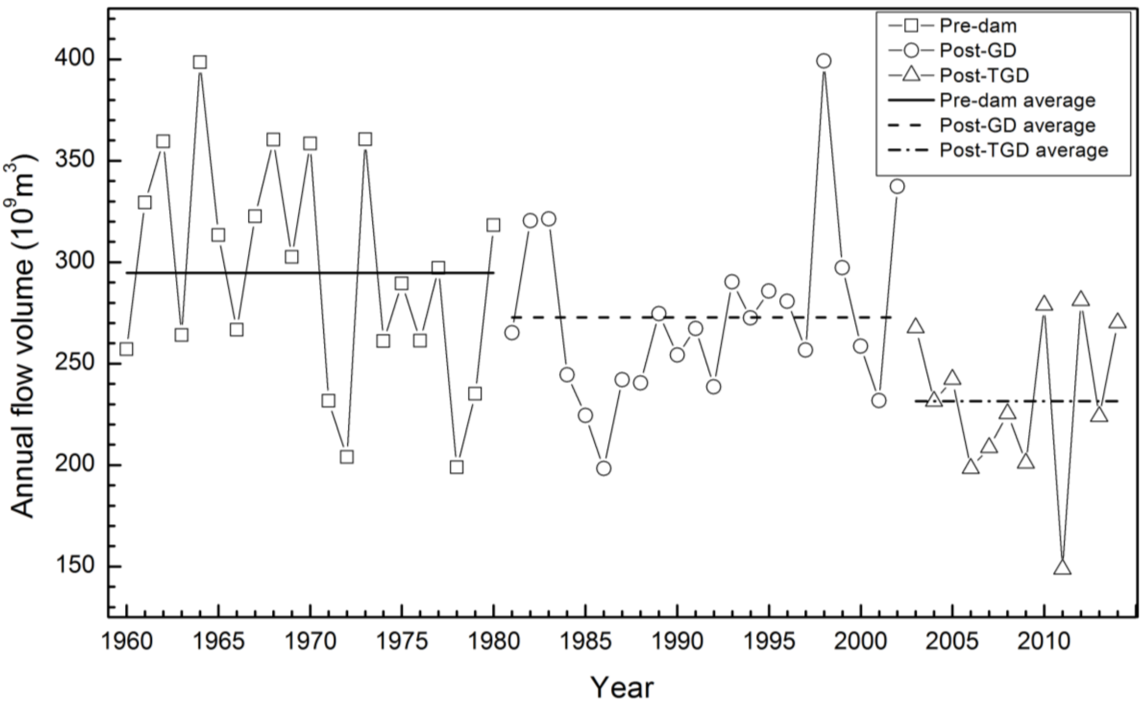


Fig. 4.6 Annual flow volume between 1960 and 2014. Lines with squares, circles, and triangles represent annual flow volume during the pre-dam (1960-1980), post-GD (1981-2002) and post-TGD (2003-2014) periods, respectively. Solid, dash, and dash dot lines represent the average values during the pre-dam, post-GD and post-TGD periods, respectively

Affected by the monsoon climate, the monthly flow had remarkably seasonal fluctuation during the benchmark period (see Fig. 3.2). The monthly mean flowrate varied from 2397 m^3/s to 191245 m^3/s. The maximum in July was almost 80 times the minimum in January. The mean flowrate was above 134685 m^3/s during the high flow period from May to September, and the corresponding total flow accounted for 66.4% of the total annual flow. The period from October to the next April was characterized by a low mean flowrate of below 101529 m^3/s. The natural seasonal fluctuation in discharge formed the basic hydrologic regime in maintaining a large water surface in the wet season, while numerous small lakes, vast mud flats, and grassy plains in the dry season. The natural seasonal hydrologic environment provided perfect habitats and sufficient nutrients for various valuable plant species, fish species and bird species.

4.3.4 Annual flow alterations

The time series of annual runoff volume from 1960 to 2014 is represented in Fig. 4.6. Compared with the pre-dam period, the post-dam annual flow was easily distinguishable. The annual mean discharge during post-GD period and post-TGD period was 8,650 m^3/s and 7,340 m^3/s, respectively, and the corresponding mean annual volume was 272.8×10^9 m^3 and 231×10^9 m^3, separately. The post-dam annual flow volume decreased dramatically and it was only higher in 4 out of 34 years. It seemed this situation even worsened following the impounding of TGD, when more upstream water was dammed. The mean annual runoff volume further decreased by 41×10^9 m^3 from post-GD period to post-TGD period, and the minimum volume decreased from 198×10^9 m^3 in 1986 to 149×10^9 m^3 in 2011. This finding agrees well with the study conducted by Mao et al. (2017), who analysed the percentage of annual runoff anomaly (annual runoff divided by the mean annual runoff from 1951 to 2011) during the period of 1951-2011 and found the annual runoff anomalies after 1986 were almost all negative except several extreme flooding years.

Considering the skewed distribution of observed daily discharge data, median value rather than mean value was adopted to characterize post-dam hydrologic alterations. The annual median flowrate and the flow anomaly over the two post-dam periods are listed in Table 4-3. It can be seen from the table that the annual median flowrate varied from 4,600 m^3/s to 12,293 m^3/s, and the flow anomalies changed between -52.53% and 26.83%. However, apart from the prominent positive anomalies in 1983 and in 1998, considerable negative anomalies can be observed over the last 34 years. Even though the great positive anomalies marginally offset the overall flow departure from the natural condition, the average flow anomaly over the post-GD period reached to -12.56%. The average flow anomaly fell sharply to -26.28% over the post-TGD period, when the flow reduced markedly in all the 12 years and no positive anomaly occurred. The average flow anomaly over the post-TGD period doubled compared to that over post-GD period, indicating an increasingly exacerbated flow alteration with the intensified human activities.

Table 4-3 Annual median flowrate and anomalies between 1981 and 2014

Water year	Discharge (m^3/s)	Anomaly (%)	Water year	Discharge(m^3/s)	Anomaly (%)
1981	8,244	-14.94	1999	8,890	-8.27
1982	9,904	2.18	2000	8,225	-15.13
1983	10,358	6.87	2001	7,545	-22.15
1984	7,805	-19.47	2002	9,885	2
1985	7,040	-27.37	2003	8,186	-15.54
1986	6,072	-37.35	2004	6,825	-29.58
1987	7,633	-21.25	2005	7,526	-22.35
1988	7,512	-22.49	2006	6,171	-36.33
1989	8,576	-11.52	2007	6,354	-34.44
1990	8,050	-16.94	2008	6,903	-28.78
1991	8,535	-11.93	2009	6,233	-35.69
1992	6,655	-31.33	2010	8,682	-10.42
1993	9,441	-2.59	2011	4,600	-52.53
1994	8,334	-14.01	2012	9,060	-6.52
1995	8,680	-10.44	2013	6,708	-30.79
1996	8,603	-11.24	2014	8,489	-12.41
1997	8,168	-15.73	(1960-1980)	9,692	0
1998	12,293	26.83			

It is noted in Fig. 4.7 that the flow duration curves were increasingly flattened with noticeable overall downward shifts following dam regulations, further confirming an overall decrease in discharge after dam regulations. The moderate fluctuation includes a dampening of peak flow and an elevation of low flow magnitude during both post-dam periods. The high flow magnitude was remarkably lowered during the post-change periods, especially in the post-TGD period. Specifically, the maximum daily flow dropped by 1,100 m^3/s and 14,300 m^3/s over the post-GD period and post-TGD period, respectively. However, low flow magnitude considerably increased compared to the natural condition, notably over the post-TGD period. The minimum daily flowrate increased by 25% during the post-GD period and 90% during the post-TGD period. Although flow exhibited overall downstream shifts following the two dam regulation periods, it was most prominent only for the high magnitude flow region. During the post-GD period, the curve showed an obviously downward shift within the 63rd percentile and a slightly upward shift afterwards. This shifting feature was more obvious during the post-TGD period, when the curve further fell to the lowest within the 87th percentile followed by a sharp remarkably upward shift to the highest. Compared to the pre-dam curve, the low flow region of the curve became flashier after TGD regulation, which might be caused by the irregular flow adjustment of the dam in dry periods to meet different operational objectives.

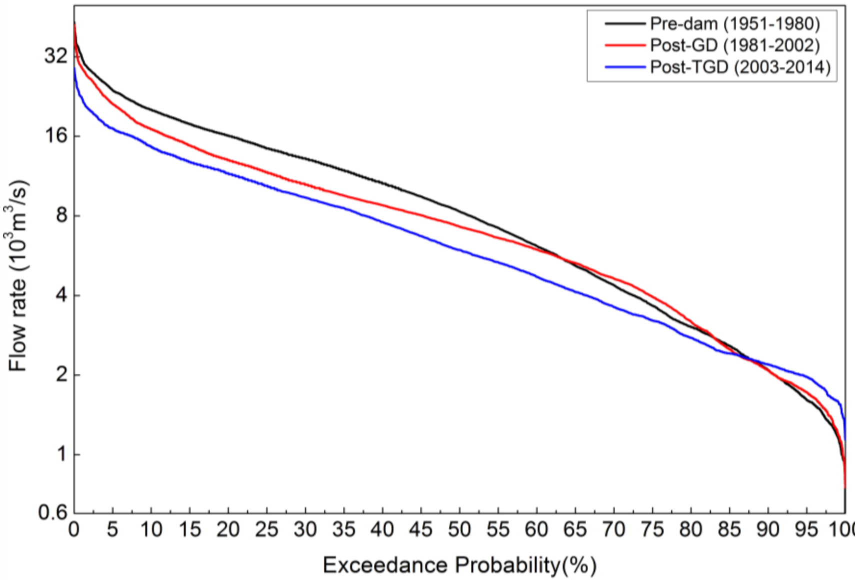


Fig. 4.7 Flow duration curves during periods of pre-dam (black colour), post-GD (red colour) and post-TGD (blue colour)

4.3.5 Monthly flow alterations

As shown in Table 4-4 and Fig. 4.8, the magnitudes of monthly median flow in Dongting Lake were substantially altered following dam regulations, and exhibited similar changing patterns over the two post-dam periods. The monthly median flow was marginally augmented from January to March, while it was reduced to various extents in the remaining nine months. The anomalies of post-dam monthly median flow to pre-dam monthly median flow reflected that the increase of monthly flow was more obvious during post-GD period, while the decrease was more obvious during post-TGD period. Although the flow anomalies from January to March seemed to be high during the two dam-impacted periods, the alteration in monthly median flow was virtually insignificant according to the Student's t-test results. Over the post-GD period, Student's t-test results revealed that significant (p<0.05) monthly flow reductions of 25.9% and 23.1% were observed in the low flow months of October and November, and 35.8% in the high flow month of May. In the remaining six months, the reductions in monthly flow were not significant. Over the post-TGD period, Student's t-test results demonstrated that significant (p<0.05) monthly flow reductions ranging from 23.1% to 55.1% were detected from May to November except June. The greatest amount of monthly flow reductions were detected in the low flow months of October and November, when the post-TGD flowrate was no more than 51% of the natural condition.

Table 4-4 Monthly median flowrates and anomalies (* indicates 95% confidence level for Student's t-test)

	Median flow (m^3/s)			Anomaly (%)	
	1960-1980	1981-2002	2003-2014	1981-2002	2003-2014
January	1,960	2,215	2,385	13.0	21.7
February	2,800	3,780	2,948	35.0	5.3
March	4,425	5,385	4,870	21.7	10.1
April	8,903	8,315	7,423	-6.6	-16.6
May	15,350	**9,855***	**11,800***	-35.8	-23.1
June	15,330	12,900	12,400	-15.9	-19.1
July	18,950	16,650	**12,000***	-12.1	-36.7
August	14,450	12,550	**9,880***	-13.2	-31.6
September	13,300	10,460	**8,800***	-21.4	-33.8
October	9,720	**7,205***	**4,955***	-25.9	-49.0
November	6,173	**4,750***	**2,775***	-23.1	-55.1
December	2,720	2,575	2,455	-5.3	-9.7

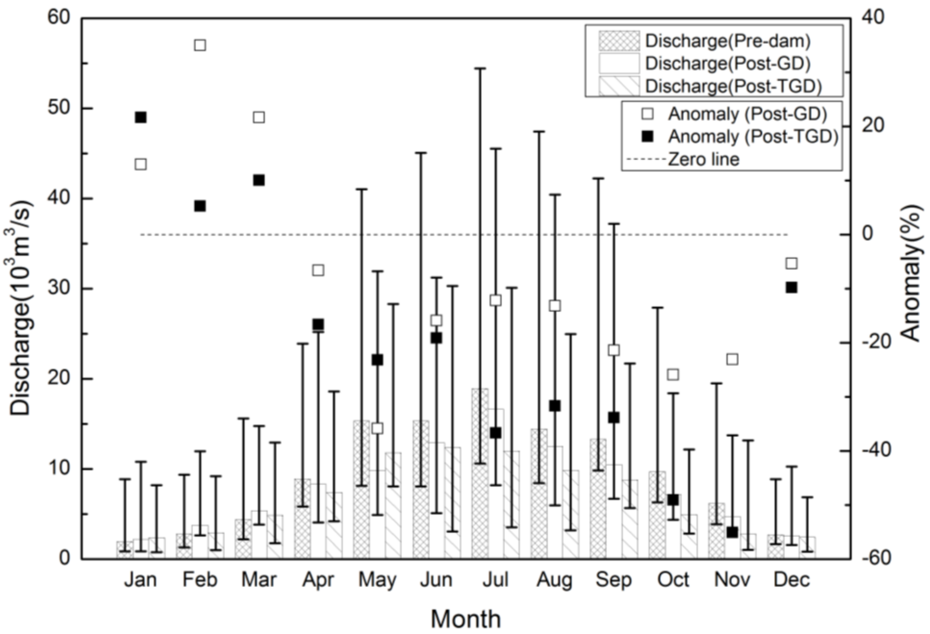


Fig. 4.8 Monthly median flowrates and anomalies during different periods (Bottom and top horizontal lines indicate the minima and maxima, respectively)

Although the magnitudes of monthly flow had been changed at the monthly scale, the seasonal distribution pattern of monthly flow was approximately maintained unchanged (Fig. 4.8), with high flow from May to September and low flow from October to the next April. However, the intra-annual distribution of flow had been severely flattened out following dam regulations, which was especially apparent for the post-TGD period. As revealed in Fig. 4.8, the distribution of post-TGD monthly median flow in the flood season became more even and steady, due to the discharge modification by the upstream dams. Moreover, the natural fluctuations of the monthly flow had been altered at the monthly scale. The amplitudes of monthly flow are shown with the maxima and minima for each month in Fig. 4.8 and the extreme ratios of monthly flow are indicated in Fig. 4.9. As illustrated in Fig. 4.8, the two post-dam periods experienced an overall decrease in the maximum and minimum monthly flows. Considerable monthly flow drops of the maxima and minima occurred in the flood season, while minor increases were observed in the dry season. Compared to the natural condition, the fluctuation extents of monthly flow were reduced notably in the majority of the twelve months during the two post-dam periods (Fig. 4.9). More considerable changes were detected during the post-TGD period, when the extreme ratios of monthly flow for all twelve months except May were prominently lower than those during both pre-dam and post-GD periods.

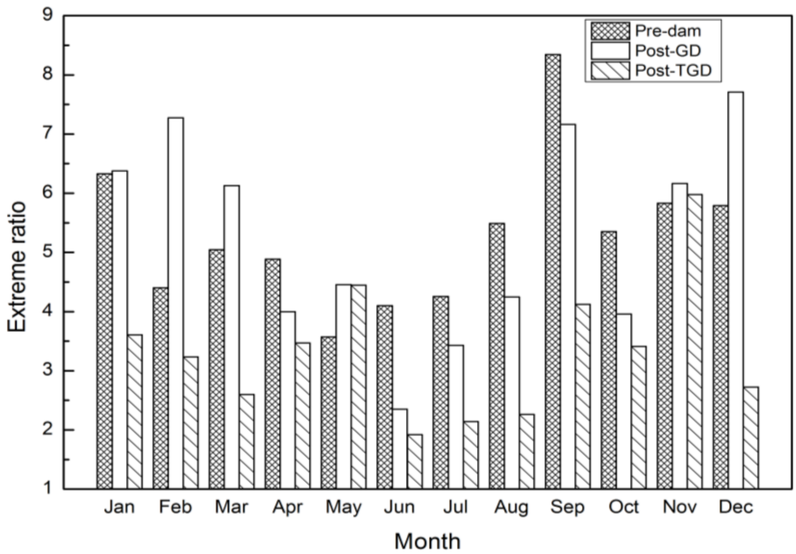


Fig. 4.9 Extreme ratios of monthly flow (maxima over minima) during different periods

4.3.6 Alterations of extreme conditions

4.3.6.1 Magnitudes and timing of annual extreme flows

The magnitudes of annual extreme flow conditions have been greatly changed over post-dam periods. The medians of annual minimum and maximum flows at daily, weekly, monthly and quarterly scales (1-, 3-, 7-, 30-, 90-day) were given in Table 4-5, Fig. 4.10 and Fig. 4.11, and their anomalies were also calculated to quantify the alterations of natural extreme flows.

Table 4-5 Median flowrates and anomalies for extreme flows (* indicates 95% confidence level for Student's t-test)

	Median flow (m^3/s)			Anomaly (%)	
	1960-1980	1981-2002	2003-2014	1960-2002	2003-2014
1-d min	1,355	1,475	1,575	8.9	16.2
3-d min	1,372	1,478	1,630	7.7	18.8
7-d min	1,432	1,513	**1,828***	5.7	27.7
30-d min	1,717	1,889	**2,224***	10.0	29.5
90-d min	3,159	3,733	3,148	18.2	-0.4
1-d max	28,550	27,100	**21,700***	-5.1	-24.0
3-d max	28,420	26,820	**21,480***	-5.6	-24.4
7-d max	27,960	25,560	**20,060***	-8.6	-28.3
30-d max	23,430	19,100	**16,570***	-18.5	-29.3
90-d max	18,950	**14,640***	**12,870***	-22.7	-32.1

As shown in Table 4-5 and Fig. 4.10, the medians of all extreme low flows increased slightly over the post-GD period, and moderately over the post-TGD period (except for the 90-day minimum). Student's t-test statistics for the pre- and post-dam periods indicated that significant increases (p<0.05) in the 7- and 30-day minimum flows were detected during the post-TGD period, while the increases in other extreme low flows were insignificant following dam regulations. Although the alteration was intensified with the increase of flow duration, it is noteworthy that 90-day minimum flow during post-TGD period remained unchanged. On the contrary, the magnitudes of all extreme high flows were changed to be marginally lower over the post-GD period and remarkably lower over the post-TGD period (Table 4-5 and Fig. 4.11). Student's t-test results revealed that the decrease in all post-GD extreme high flows were insignificant except for the 90-day maximum, while all post-TGD extreme high flows decreased significantly (p<0.05) compared with the pre-dam conditions. Compared with the natural conditions, the medians of extreme high flows were approximately 5%~23% lower over the post-GD period and 24%~32% lower over the post-TGD period. The changes in maxima and minima of each extreme high and low flow indicated that the amplitudes of all extreme flow (except for the post-GD 90-day minimum) were diminished during the post-GD period, and more considerably during the post-TGD period (Fig. 4.10, Fig. 4.11). The diminished amplitudes of extreme flows indicated the extreme low and high flows over different temporal scales were maintained within more stable fluctuation ranges.

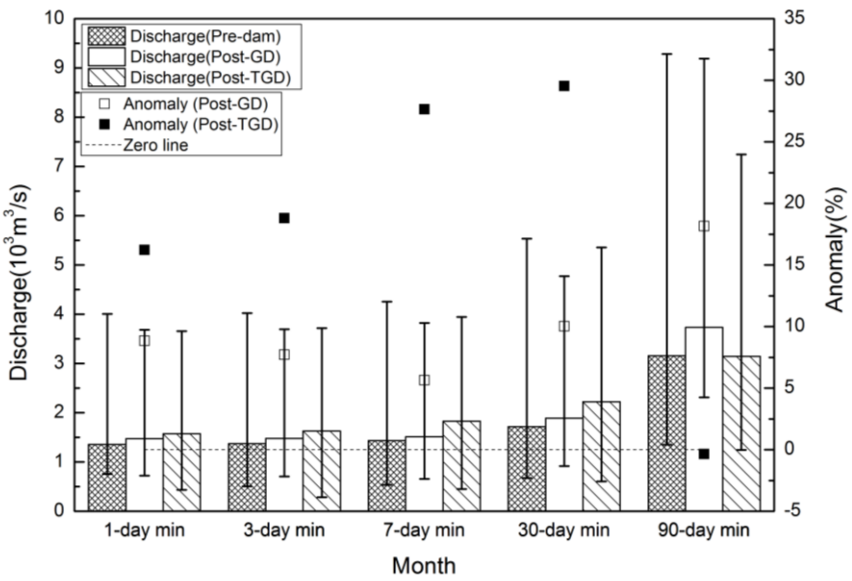


Fig. 4.10 Medians and anomalies of extreme low flows during different periods (Bottom and top horizontal lines indicate the minima and maxima, respectively)

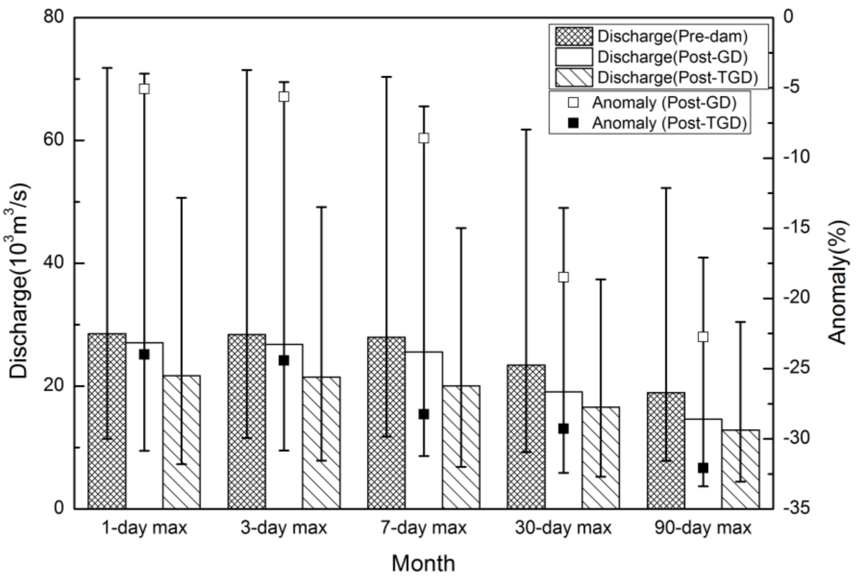


Fig. 4.11 Medians and anomalies of extreme high flows during different periods (Bottom and top horizontal lines indicate the minima and maxima, respectively)

Except for magnitude changes in annual extreme flows, the timing of annual extreme low and high flows has also been altered. To better understand the timing alteration of annual extreme flows, the temporal percentiles (25%, 50% and 75%) as well as the minimum (the earliest timing) and maximum (the latest timing) of Julian dates of annual 1-day extreme flows were calculated and given in Table 4-6. For the timing of annual 1-day minimum flow, the earliest and latest occurring time stayed unchanged, while the percentiles showed some changes during the two post-dam periods. And the timing alteration in daily extreme low flow was more severe over the post-TGD period. Specifically, 50% of the 1-day minimum flow occurred on the Julian date of 15th in the pre-dam period. It was advanced during both post-dam periods, with 14 days earlier over the post-GD period and 27 days earlier over the post-TGD period. This finding is well consistent other researchers' results. Feng et al. (2013) found that the average starting date of the dry season of Dongting Lake wetland was 3.42 days year−1 earlier during 2004-2009 than that during the period of 2000-2002. Liang et al. (2012) found it was 18 days earlier during the period of 2003-2010 than that during the period of 1981–2002. Concerning the timing of annual 1-day maximum flow, the earliest and the latest occurring time, as well as the three percentiles were slightly postponed during the two dam-impacted periods. Comparison between the two post-dam periods indicated that the timing alteration of extreme daily high flow was less severe over the post-TGD period, except that the latest occurring time during the post-TGD period was postponed by 62 days behind the post-GD period. Although timing alterations of daily extreme low and high flow existed following the two dam-impacted periods, no significant changes were detected according to the Student's t-test results.

Table 4-6 Timing of annual extreme water conditions

	Julian date of 1-d minimum			Julian date of 1-d maximum		
	1960-1980	1981-2002	2003-2014	1960-1980	1981-2002	2003-2014
25%	366	363	316	158	177	162
50%	15	1	353	189	193	185
75%	40	7	6	205	211	205
min	1	1	1	117	159	141
max	366	366	366	259	255	317

4.3.6.2 Frequency and duration of high and low pulses

The frequency of low flow pulse during the two post-dam periods increased, whereas the frequency of high flow pulse, and the durations of low and high pulses generally decreased. The frequency and duration of high and low pulses at various temporal percentiles (25%, 50% and 75%) and the minimum and maximum values are listed in Table 4-7. The statistics in the table suggest alterations in low and high pulses were mostly more obvious during the post-TGD period for the three percentiles as well as the minimum and maximum values. As verified by Student's t-test, significant changes ($p<0.05$) were only detected for the low pulse count and duration of high pulse over the post-TGD period, while alterations in the frequency and duration of high and low pulses over the post-GD period were insignificant. The maximum low pulse count was well maintained at the natural value over the post-GD period, but was doubled over the post-TGD period. Concerning the maximum high pulse duration, it decreased from 190 days before the dam regulation to 37 days over the post-GD period, and further decreased to 29 days over the post-TGD period. However, the medians of low pulse duration and high pulse counts were equal or almost equal, indicating no further alteration occurred over the post-TGD period.

Table 4-7 Frequency and duration of high and low pulses

	Number of low pulse			Duration of low pulse (day)			Number of high pulse			Duration of high pulse (day)		
	1960 - 1980	1981 - 2002	2003 - 2014	1960 - 1980	1981 - 2002	2003 - 2014	1960 - 1980	1981 - 2002	2003 - 2014	1960 - 1980	1981 - 2002	2003 - 2014
25%	2	1	3	13	6	7	3	3	2	9	8	5
50%	2	3	4	26	11	12	5	4	4	13	9	7
75%	4	4	7	58	44	27	6	4	6	24	20	12
min	0	0	1	4	2	2	1	1	0	5	4	3
max	6	6	12	94	164	127	8	7	7	190	37	29

Changes in the number of discharge reversals and rise and fall rates of the hydrograph were also found in the lake over the two post-dam periods (Table 4-8). Overall, the lake showed no obvious alteration in the number of reversals and rise and fall rates over the post-GD period, yet it experienced significant decreases ($p<0.05$) in the rise and fall rates, and a significant increase ($p<0.05$) in the number of reversals over the post-TGD period. Such changes can be generally detected from the three percentiles (25%, 50% and 75%) and minimum and maximum values of the rise and fall rates. The median of rise rates decreased by 40 m^3/s/day over the post-GD period and by 125 m^3/ s/day over the post-TGD period, with corresponding reductions of 10% and 32%, respectively. For the fall rates, an insignificant increase was observed over the post-GD period, while a prominent decrease was detected over the post-TGD period, indicating inconsistent changing patterns during the two dam-impacted periods. Following dam regulations, the number of hydrograph reversals exhibited an enormous increase in the 75th percentile and the maximum values over the post-TGD period, which were almost doubled compared with the natural situation.

Table 4-8 Rate and frequency of water condition changes

	Rise rate (m^3/s/day)			Fall rate (m^3/ s/day)			Number of reversals		
	1960-1980	1981-2002	2003-2014	1960-1980	1981-2002	2003-2014	1960-1980	1981-2002	2003-2014
25%	304	269	220	-300	-306	-240	43	46	49
50%	395	355	270	-273	-290	-225	49	50	54
75%	413	406	310	-218	-234	-196	54	56	102
min	220	200	120	-400	-385	-360	29	41	46
max	500	500	320	-150	-200	-100	66	68	115

4.3.7 Discussion

4.3.7.1 Potential impacts on lake management and protection

The altered flow regimes in Dongting Lake have posed potential challenges for water resources management and wetland protection in Dongting Lake. The predominantly decreased annual flow in the lake has triggered problems including long-term water unavailability, lake shrinkage with declining water level, and degradation of swamp wetlands.

As documented by Hu et al. (2015b), the area of mudflat and water bodies in the lake decreased dramatically from 750.9 km^2 in 2000 to 493.3 km^2 in 2012, falling to the lowest of 390.6 km^2 in 2009.

Changes in monthly flow have both positive and negative effects on the lake management. The decreased monthly flow in the flood season benefits flood control in the lake area and the increased monthly flow in spring helps alleviate spring droughts. However, the decreased monthly flow in dry period has resulted in navigation difficulties, reduced crop yields and water supply problems over the lake area in recent years (Gao et al., 2012). Moreover, the natural seasonal hydrologic environment provided ideal habitats and sufficient nutrients for various valuable plant species, fish species and bird species. The alteration in monthly flow, especially the reduced flow in dry period, might induce the reduction of habitat due to the modified surface and subsurface water levels, and changes in the natural flooding of floodplains and terminal wetlands in the lake. In the East Dongting Lake, both the rates of vegetation expansion and the minimum elevation of vegetation covered area decreased rapidly due to the considerably decreased monthly flow from July to November following the impounding of TGD (Xie et al., 2015). Besides, affected by the reduced flood water level and increased low water level, the grass marshlands are likely to be exposed earlier and longer than habitually (Hu et al., 2015b).

The magnitude of changes in extreme flow conditions might have some potential geomorphic and ecological effects. According to Graf (2006), the instantaneous, daily and monthly extreme flows are related to the sediment processes, channel morphology and floodplain changes. Following dam regulations, the downstream, including the three inlet channels of Dongting Lake which connect the lake with the Yangtze River, might suffer from erosion and riverbed instability because of the reduced peak discharge and sediment concentration (Li et al., 2011). Moreover, the altered magnitudes of extreme flow conditions may cause ecological consequences in the lake. The dampened peak discharge and uplifted low flow lead to less flow flashiness, which might cause shifts in community composition and decreases in species richness (Poff and Zimmerman, 2010). The more even flow variabilities may favour non-native species and reduce macroinvertebrate abundance and diversity (Poff and Zimmerman, 2010, Gao et al., 2012). Field investigations conducted by Zhang et al. (2014b) pointed out that the striped field mouse and the Norway rat, which rarely inhabited in the Dongting Lake area before TGD regulation, suddenly became abundant on the lake beach after the impounding of TGD. Besides, higher extreme low flows imply a higher water table during the dry season, hence affecting the riparian vegetation in the lake areas (Sparks, 1995). As a result, the richness and abundance of fish and waterbird species, as well as wetland vegetation in the lake might be greatly affected by the flow alteration.

Also, the alterations in frequency and duration of high and low pulses might alter the mobility or stability of the lake bed and bank materials and change sedimentation processes like bedload transport, erosion and deposition processes in the lake (Graf, 2006). It should be noticed that the changes in frequency and duration of high flows might modify the magnitudes of transported nutrients and suspended organic matter, therefore the food webs might be altered (Doyle et al., 2005). As the timing of extreme high flows is critical for fish spawning and larval survival, the timing alteration might cause losses of cues for fish spawning and migration (Hu et al., 2008). However, the impact of the timing alteration of extreme flows on the lives of fish in Dongting Lake is still not clear. Usually, the magnitude and frequency of changes in marginal aquatic and riparian habitats substantially depend on the rise and fall rates and number of hydrologic reversals (Richter et al., 1996). The significant changes in the flow rates and frequency over the lake might alter the wetland habitat dramatically and lead to a decrease in organisms and native species, which have been well adapted to the longstanding natural flow conditions.

4.3.7.2 Possible dam influence on the hydrological alterations

The operation of GD and TGD has adjusted the lake-river relationship between Dongting Lake and the Yangtze River, by affecting both the inflow from the Yangtze River to the lake through the three inlets, and the outflow from the lake to the river. Since the dam has retained a large amount of sediment, the riverbed downstream of the dam has been undercut, thus water level in the river has dropped. The lowered water level in the river decelerates water flowing from the river into the lake through the three lake inlets, while it accelerates water flowing from the lake to the River through the only outlet Chenglingji (Ou et al., 2014). Records have shown that the annual runoff in the three lake inlets has reduced gradually since the impoundment of TGD (Chang et al., 2010, Zhang et al., 2015a, Zhou et al., 2015).

Meanwhile, flow regime changes in Dongting Lake are largely dependent on the operational modes of the dams (Gao et al., 2012, Yu et al., 2013). The variation pattern of monthly median flow follows the seasonal water impounding and releasing of the dams, and the magnitude of variation is determined by the extent of dam impounding or releasing. From January to March, the monthly flow has become marginally higher than the natural situation, when more water is released from the dams for water supply and preparation of flood controlling purposes. Afterwards, more water is retained in the huge dams for flood prevention or water impounding purposes, therefore the peak discharge in the lake is remarkably diminished and the monthly flow is accordingly reduced. The significant decreases in the 1 through 90 day maximum flows may benefit flood control and alleviate sedimentation problem in the lake area, which can be confirmed by Zhou et al. (2015), who found the flowrate and sediment deposition amount has decreased dramatically under the flood control mode of dam, and the lake changed from a siltation dominant to erosion-dominant state under the remaining three dam operational modes (pre-discharge, water supplement and water storage modes).

Except for upstream dam regulations, potential drivers like land cover changes, climate variability and increasing water consumption, which may possibly compound or counter the influences of dam regulations, should also be considered in further exploring the reason for hydrologic alterations in the lake. In this study, the post-TGD data adopted were only for 12 years (2003-2014). As it is preferable to use greater than 15 years of post-dam data (Graf, 2006), study should continue after the availability of more observed data.

4.4 Conclusions

In this chapter, the flow regime in Dongting Lake from 1960 to 2014 is investigated. Firstly, flow regime changes in Dongting Lake under different TGD operational modes based on observed daily water level and discharge data from 8 locations spanning from 1960 to 2010 is quantified. Results show that flow in Dongting Lake has significantly reduced following TGD regulation under flood-control mode and water-storage mode, with a maximum discharge reduction of 6,173 m^3/s and water level reduction of 1.85 m. Under water supplement and pre-discharge modes, water level has increased after dam regulation, with a maximum increase of 1.5 m in March, while the increase in discharge is not significant. Water level-discharge rating curves and flow duration curves were constructed to identify pre- and post-dam flow conditions under different operational modes. Under dam operation, water flowing from the Yangtze River to Dongting Lake through the Three Channels has been moderated, thus flow in the lake is moderated as well. Flow regulation imposed by TGD appears to have flattened Dongting Lake's discharge under all four dam operational modes, especially under water-storage mode, when high magnitude flows have been remarkably reduced. Flow duration curves with dam regulation are far below natural situation under each mode except water-supplement mode, when water is drained downstream and thus flow in the lake is slightly elevated. Relationships between water level and discharge have also been altered, with discharge decreases at the same water level following TGD operation under all modes. These conclusions will have significant implications to the sedimentation dynamics and wetland management of Dongting Lake.

Furthermore, the hydrologic alterations of Dongting Lake are fully characterized by dividing the whole study period of 1960-2014 into three periods (pre-dam period of 1960-1980, post-GD period of 1981-2002, post-TGD period of 2003-2014) based on the starting time of dam regulation of GD and TGD, and then using a set of hydrologic metrics to investigate the pre- and post-dam hydrologic changes in flow magnitude, frequency, duration, timing and rate of change. The analytical results show that the annual flows are noticeably lower in post-dam periods, and monthly flows are also reduced except from January to March, when monthly flows are marginally augmented. Slight increases in the 1 through 90 day minimum flows and significant decreases in the 1 through 90 day maximum flows are detected, along with increasing changing magnitude corresponding to increasing duration. The conclusion of increases in minimum flows and decreases in maximum flows detected by IHA further confirms the results from flow duration curves and rating curves in section 4.2, which reveals that flow in Dongting Lake has been dampened. As for the timing of annual extreme low flow, it is marginally altered while not obviously changed for extreme high flow. Other significant alterations include changes in the number and duration of high and low pulses, lower rate of hydrograph rise and fall, and a higher number of hydrograph reversals. All the flow metrics exhibits similar variabilities during the two post-dam periods, and the alterations are more severe following the impoundment of Three Gorges Dam. This study provides a good representation in comprehensively exploring flow regime changes for dammed catchments, particularly where the water resources are scarce and the ecosystem is fragile.

It should be noted that the observed flow regime changes should be the combined effects of climate and human impacts. To confirm which factor plays the primary role in altering the hydrological conditions in Dongting Lake, scientific approach should be adopted to quantitatively separate the impact of climate change and variability from the impact of human activities.

5 ESTIMATING THE IMPACT OF CLIMATE VARIABILITY AND HUMAN ACTIVITIES ON STREAMFLOW VARIATION

5.1 Introduction

The hydrological processes are primarily driven by climate and strongly affected by human activities. Streamflow is affected by climate mainly through precipitation and potential evaporation. Streamflow can also be altered by human activities including land use/cover change, large impoundments and direct water extraction. While many studies quantify the combined effects of climate and human activities on streamflow, it is important to identify how much of the streamflow is altered from climatic factors versus human activities. Such information may be used for water resources management and disaster prevention and mitigation depending on whether climate or human beings are the primary factor altering streamflow. Therefore, the aim of this chapter is to quantify the relative impact of climate and human activities on streamflow in Dongting Lake basin.

Specifically, the Budyko-based decomposition and runoff sensitivity methods are used to quantify the respective impact of climatic variations and human activities on streamflow alteration for the four sub-basins (Xiangjiang, Zishui, Yuanjiang, and Lishui) as well as the whole Dongting Lake basin rather than only the main Dongting Lake area. Firstly, the whole Dongting Lake basin is divided into five sub-basins (Xiangjiang, Zishui, Yuanjiang, Lishui, and the Main Lake) and the long-term hydro-meteorological datasets including streamflow, precipitation and climate data are employed to assess the hydro-climate changes over the four sub-basins and the main Dongting Lake area over the past 55 years (1960-2014). Secondly, the abrupt and trend changes of streamflow over the sub-basins and the whole basin are detected to spatially identify the un-impacted period and impacted periods. Thirdly, the Budyko curves are established spatially for the un-impacted period to reconstruct the relationship between dryness index (mean annual potential evapotranspiration to mean annual precipitation) and evaporation ratio (mean annual evapotranspiration to mean annual precipitation) under the natural scenario. Based on the Budyko curves, the sensitivity of streamflow to the respective changes in long-term precipitation and potential evaporation are spatially quantified using the two Budyko-based methods. Then, the results of the two methods are compared and the sensitivity characteristics of streamflow over the sub-basins and the whole lake basin are presented and discussed.

5.2 Methodology

5.2.1 Statistical analysis for breakpoint and trend detection

5.2.1.1 Pettitt's test and cumulative anomalies for breakpoint detection

In order to detect the abrupt changes in the hydro-meteorological datasets over the five study regions, the non-parametric approach developed by Pettitt (1980) is applied in this study. The Pettitt's test is more sensitive in detection of a single shift at an unknown point in time (Wijngaard et al., 2003), thus it is commonly used to identify the single change point in continuous hydrological or meteorological data. The test assesses the null hypothesis H_0 implying that the data follow one or more distributions are homogeneous with the same location parameter, against the alternative hypothesis H_1 implying that a change point causing a shift of the location parameter exists at particular time *t*. If the hypothesis H_1 is accepted, the distribution of the random variables from x_1 to x_t would be different from the distribution of the random variables from x_{t+1} to x_T. The test adopts a version of the rank-based Mann–Whitney statistic $U_{t,,T}$ (Nadim, 2008) to identify the time when a shift of the location parameter occurs at an unknown time *t*. The test statistic is defined as

$$K_T = max_{1 \le t \ll T} \left| U_{t,T} \right|, \qquad (5\text{-}1)$$

where

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sgn(x_i - x_j) \quad (5\text{-}2)$$

where x_i to x_j are random variables with x_i following x_j in time.

A shift occurs at time t if the statistic K_T is significantly different from zero at a given level. The significance probability of K_T for $p \leq 0.05$ is given as

$$p \cong 2exp\{-6(K_T)^2/(T^3 + T^2)\} \quad (5\text{-}3)$$

To validate the results from Pettitt's test, the cumulative anomaly method is executed by summing the annual departures of the average for hydro-meteorological variables and plotting the resulting time sequence through to the present. The cumulative anomaly method can effectively filter some high frequency "noise" without losing the actual signal, thus serving as an additional approach to discriminate the abrupt change-points of a time series.

5.2.1.2 Mann–Kendall test for trend detection

In order to study the temporal variation of the hydro-meteorological variables, the nonparametric Mann–Kendall method (Mann, 1945, Kendall, 1975) is used to detect the trends during the analysis periods, which are split from the whole study period of 1960-2014 based on the Pettitt's test results. The Mann–Kendall test is highly recommended by the World Meteorological Organization (Mitchell et al., 1966) and is widely used to detect the significance of monotonic trends in climatological and hydrological data time series. It is based on the test statistic S, which is given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i) \quad (5\text{-}4)$$

where n is the length of data set, x is the data point at times i and j $(j > i)$ and the sign function is given as:

$$sign(x_j - x_i) = \begin{cases} +1 & x_j > x_i \\ 0 & x_j > x_i \\ -1 & x_j < x_i \end{cases} \quad (5\text{-}5)$$

The variance of *S* is computed by:

$$\mathrm{var}(S) = \left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i i(i-1)(2i+5) \right] / 18 \quad (5\text{-}6)$$

where t_i is the number of ties of extent i and m is the number of tied rank groups. For n larger than 10, the standard normal test statistic Z is computed as the Mann–Kendall test statistic as follows:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{var}(S)}} & S > 0 \\ 0 & S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{var}(S)}} & S < 0 \end{cases} \quad (5\text{-}7)$$

A positive S value indicates an upward trend and a negative value indicates a downward trend. The Z value is implied to evaluate the presence of a statistically significant trend. In a two-sided test for trend, the null hypothesis of no trend should be accepted if $|Z| \le Z_{a/2}$ at the level of significance.

5.2.2 Separating the effects of climatic variability and human activities on annual streamflow

5.2.2.1 Fu's Budyko framework

The water balance for a basin can be expressed as Q = P-E-ΔS, where Q is the streamflow, P is the precipitation, E is the actual evapotranspiration, and ΔS is the change in water storage. ΔS can be ignored over a long period of time (Roderick and Farquhar, 2011) and it is assumed to be 0 at the mean annual scale for steady-state of water balance in the Budyko framework (Donohue et al., 2007), thus Q can be estimated as the difference between P and E. The Budyko framework (Budyko, 1958, Budyko, 1974) is established to show the partitioning of precipitation into evapotranspiration and streamflow by considering the water-energy balance in large basins (>1000 km^2) over long-term periods (≥1 year). Budyko (1974) proved that the long-term average ratio of mean annual evaporation to mean annual precipitation (evapotranspiration ratio, *E/P*), is largely controlled by the long-term average ratio of mean annual potential evaporation to mean annual precipitation (climatic dryness index, E_p/P). In basins where $E_p/P \leq 1$, energy supply from the atmosphere is the limiting factor, while in basins where $E_p/P \geq 1$, water supply is the limiting factor. All our study regions are energy-limited with $E_p/P \leq 1$.

Among various empirical equations representing the Budyko framework, the functional form proposed by Fu (1981) in Chinese and translated by Zhang et al. (2004) in English has been widely demonstrated to be an appropriate analytical equation describing the relationship between *E/P* and E_p/P for diverse basins (Yang et al., 2008a, Patterson et al., 2013, Liang and Liu, 2014, Zeng and Cai, 2015). Fu's equation can be expressed as follows:

$$\frac{E}{P} = 1 + \frac{E_p}{P} - \left[1 + \left(\frac{E_p}{P}\right)^w\right]^{\frac{1}{w}} \quad (5\text{-}8)$$

Where w is a basin-specific parameter considering the integrated effects of basin characteristics (such as vegetation type, soil properties, and topography) on evapotranspiration (Fu, 1996, Zhang et al., 2004). Each basin has a slightly different w that fits along a unique Budyko curve for the relationship between E/P and E_p/P.

5.2.2.2 Budyko-based decomposition method

According to the observed streamflow during the impacted and pre-change periods, total alteration in mean annual streamflow (ΔQ^T) can be calculated as the difference between average observed annual streamflow during the impacted period (Q_i) and average observed annual streamflow during the natural period (Q_n) as below:

$$\Delta Q^T = Q_i - Q_n \quad (5\text{-}9)$$

The change in mean annual streamflow contains changes in the mean annual streamflow due to climatic factor (ΔQ^c) and human impact (ΔQ^h), respectively:

$$\Delta Q^T = \Delta Q^c + \Delta Q^h \quad (5\text{-}10)$$

The Budyko decomposition method proposed by Wang and Hejazi (2011) is used in this study to separate the climate and direct human impacts on total mean annual streamflow change. The decomposition method assumes that changes in climate (E_p/P) can cause the change in evapotranspiration ratio (E/P), and hence induce the basin to evolve to a new state but will still follow the same Budyko curve as in the pre-impacted period (from A to C in Fig. 5.1). The basin can move along the Budyko curve with both horizontal and vertical shifts only because of climate change, whilst human effects can only cause a vertical shift to the basin. Accordingly, the impacts of climate change on annual streamflow can be predicted by the Budyko curve and the effects of basin characteristics can be estimated by the deviations from the Budyko curve. Therefore, by comparing the changes in the relationships of E/P to

E_p/P for a basin between the pre-impacted period and the post-impacted period, the impacts of changes in climate and human interferences on annual streamflow can be quantitatively separated. Since Q=P(1-E/P), if E/P decreases, then Q increases and vice versa. ΔQ^c, the climate-induced streamflow increases or decreases as move along the curve; ΔQ^h, the human-induced streamflow increases or decreases as move vertically off the curve.

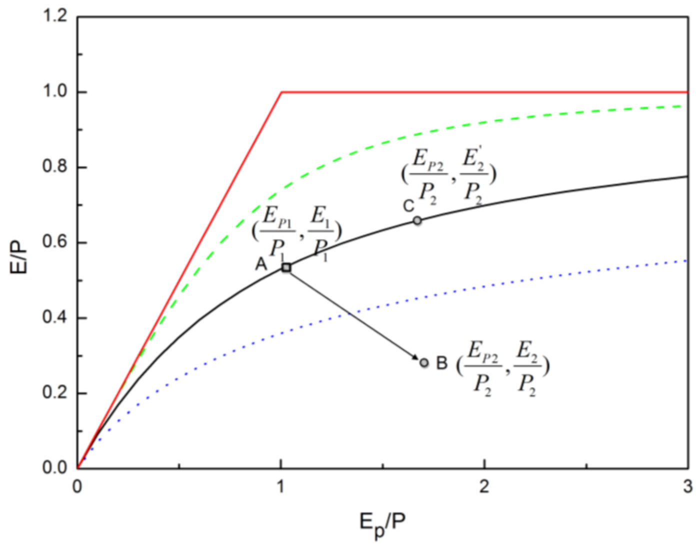


Fig. 5.1 Budyko-based decomposition method to separate the climate and human impacts on streamflow. Points A, B, C are the coordinates for climatic dryness index (E_p/P) and the evapotranspiration ratio (E/P). Under the combined effects of climate impacts and human interferences, the coordinate shifts from point A to point B. Under climate change only, the coordinate evolves from point A to point C along the Budyko curve

As human interferences cause a vertical shift from E_2'/P_2 to E_2/P_2, the magnitude of the direct human-induced change of the streamflow (ΔQ^h) is given by:

$$\Delta Q^h = P_2\left(\frac{E_2'}{P_2} - \frac{E_2}{P_2}\right) \tag{5-11}$$

The climate change contribution to streamflow change can be computed by deducting the human-induced change from the total streamflow change:

$$\Delta Q^c = P_2\left(1 - \frac{E_2'}{P_2}\right) - Q_1 \qquad (5\text{-}12)$$

By substituting Fu's equation ((5-8) into equation (5-12), the following is obtained:

$$\Delta Q^c = \left(P_2^w + E_{p2}^w\right)^{\frac{1}{w}} - E_{p2} - Q_1 \qquad (5\text{-}13)$$

5.2.2.3 Budyko-based streamflow sensitivity method

As indicated by the Budyko framework, mean annual precipitation and potential evapotranspiration are the two dominant factors affecting the water balance. Perturbations in precipitation and potential evapotranspiration can cause responses to annual streamflow. The climate contribution to the mean annual streamflow change can be approximated by the Budyko-based streamflow sensitivity or elasticity method regarding to precipitation and potential evapotranspiration. According to Koster and Suarez (1999) and Milly (2002), the climate-induced change in mean annual streamflow can be determined by:

$$\Delta Q^c = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial E_P}\Delta E_P \qquad (5\text{-}14)$$

where ΔP and Δ E_p are changes in mean annual precipitation and potential evapotranspiration, respectively; and $\frac{\partial Q}{\partial P}$ and $\frac{\partial Q}{\partial E_P}$ are the streamflow sensitivity coefficients to precipitation and potential evapotranspiration, respectively. They can be computed from Fu's equation ((5-8) as follows:

$$\frac{\partial Q}{\partial P} = P^{(w-1)}({E_P}^w + P^w)^{\frac{1}{w}-1} \qquad (5\text{-}15)$$

$$\frac{\partial Q}{\partial E_P} = E_P{}^{(w-1)}(E_P{}^w + P^w)^{\frac{1}{w}-1} - 1 \quad (5\text{-}16)$$

The direct human-induced change of streamflow (ΔQ^h) can be calculated by subtracting the climate-induced change (ΔQ^c) from the total change in streamflow (Q_2-Q_1).

The contribution of climatic factor and human activities to the changes in streamflow can be expressed as:

$$\eta_c = \frac{\Delta Q^c}{|\Delta Q^c| + |\Delta Q^h|} \times 100\% \quad (5\text{-}17)$$

$$\eta_h = \frac{\Delta Q^h}{|\Delta Q^c| + |\Delta Q^h|} \times 100\% \quad (5\text{-}18)$$

Where η_c and η_h are the percentages of the impact of climatic factor and human activities on streamflow, respectively.

5.3 Results and discussions

5.3.1 Hydro-climatology over the 5 study regions

The long-term average (1960-2014) hydro-climatology shows slight discrepancy over the 5 study regions (Fig. 5.2). Xiangjiang sub-basin has the highest annual precipitation, actual evapotranspiration, potential evapotranspiration and temperature among the 5 study regions, while its annual runoff depth is only higher than runoff depth within Yuanjiang sub-basin. Lishui sub-basin has the lowest actual evapotranspiration, potential evapotranspiration and temperature, whilst its runoff depth is the highest. Annual precipitation varies between 1305 and 1491 mm yr^{-1} over the 5 regions, with Yuanjiang and Lishui much lower than the remaining 3 study regions. The maximum difference in annual runoff depth is between Lishui and Yuanjiang, with the former 177 mm yr^{-1} higher than the latter. Based on the water balance within the study regions, annual actual evapotranspiration is the highest over Xiangjiang whilst the lowest over Lishui, with a difference of 238 mm yr^{-1}. Annual mean temperature exhibits notably spatial difference with lower temperature within Yuanjiang and Lishui sub-basins and higher temperature within the rest three study regions. The greatest temperature difference is found between Xiangjiang and Lishui sub-basins, with annual temperature over Xiangjiang is 1 ℃ yr^{-1} higher than that over Lishui. Although affected by annual temperature, annual potential evapotranspiration shows no distinct difference among the 5 study regions. This might be that factors such as sunshine hours, actual vapour pressure, and wind speed are also the driving forces for potential evapotranspiration.

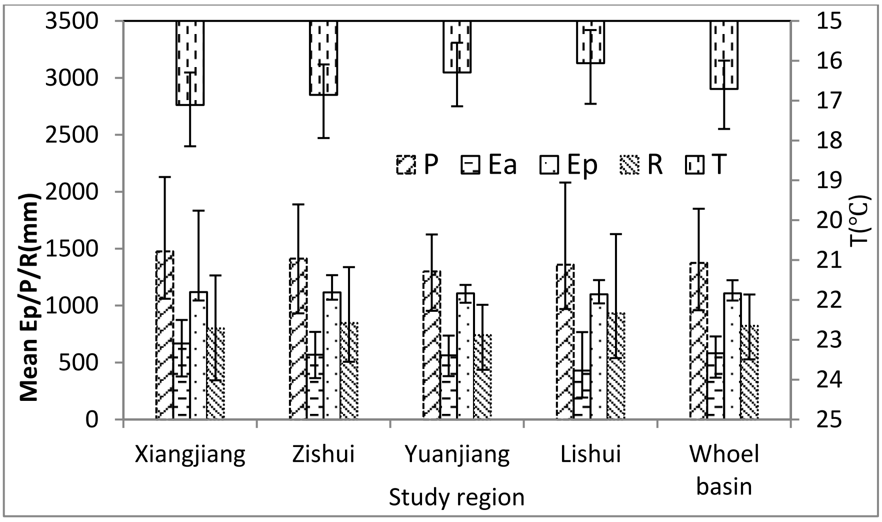


Fig. 5.2 Long-term annual P, E_a, E_p, R and T over 5 study regions during 1960-2014. (bars indicate median values, and bottom and top horizontal lines indicate the minima and maxima, respectively)

The annual hydro-climatological variables also show different temporal variation patterns over the 5 study regions. To examine their anomalies, the departure of annual hydro-climatology from the long-term average (1960-2014) is divided by the corresponding long-term average. To further reveal the underlying unadulterated form of the data, 5 points adjacent averaging smooth method (5 pts AAV smooth) is adopted to remove the “noise” of short-term random variations. Fig. 5.3 illustrates the time series of annual precipitation and streamflow anomalies and the smoothed data using the 5 pts AAV smooth over the 5 study regions. For the same time and study region, although annual precipitation and annual runoff depth have the same direction of departure, annual runoff depth shows more prominent abnormal fluctuation with higher anomalies. This implies that precipitation contributes largely to streamflow, yet streamflow is also affected by other factors like evapotranspiration, basin characteristics and human activities. When comparing the 5 study regions, it can be found that Xiangjiang and Zishui sub-basins have similar temporal patterns in annual precipitation and streamflow anomalies as depicted by the smoothing curves in Fig. 5.3 (a) and (b). Annual precipitation and runoff depth in both study regions mainly display negative anomalies during the last 55 years except positive anomalies during the period 1992-2002. As for Yuangjiang and Lishui sub-basins (Fig. 5.3 (c) and (d)), annual precipitation in both sub-regions fluctuates slightly around the long-term average with alternate positive and negative anomalies during the period 1960-2014. By contrast, annual streamflow in Yuangjiang departs from the long-term average with larger amplitudes. Additionally, since Whole basin includes the five sub-basins (Xiangjiang, Zishui, Yuanjiang, Lishui, and the Main Lake), annual precipitation and streamflow over Whole basin (Fig. 5.3 (d)) are the combined effects of the five sub-basins. It can be noted from Fig. 5.3 that annual streamflow over Whole basin generally has predominantly positive fluctuation before 1975, while this variation is not obvious in Xiangjiang, Zishui and Lishui, indicating that the positive anomalies over Whole basin is considerably attributed to Yuanjiang and Main Lake. According to the smoothing curve, variation of annual precipitation anomalies over Whole basin is similar to that over Zishui sub-basin.

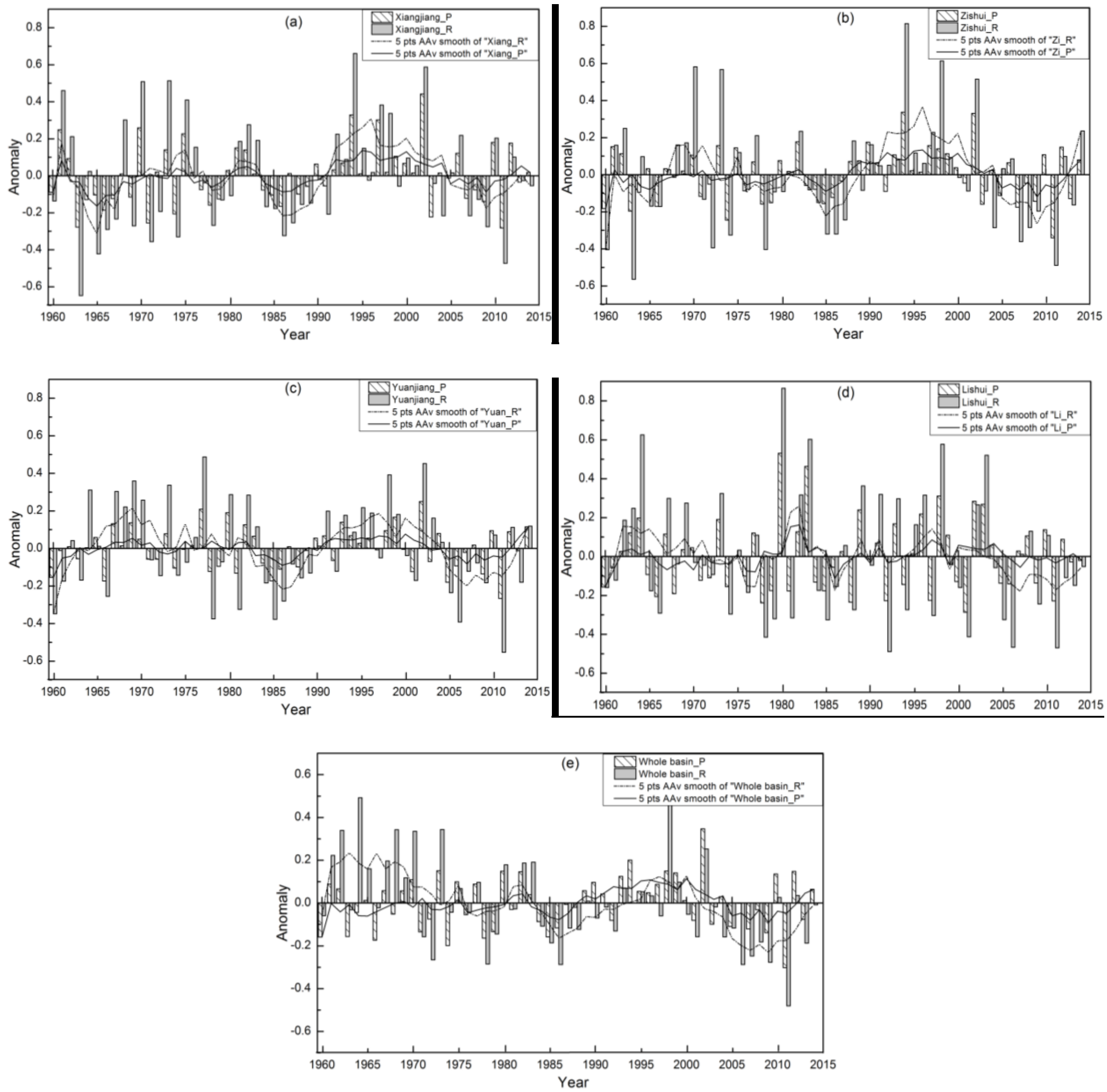


Fig. 5.3 Variation of annual precipitation (P) and runoff depth (R) anomalies and the 5 pts AAV smooth results over the 5 study regions during 1960-2014

5.3.2 Breakpoint and trend detection

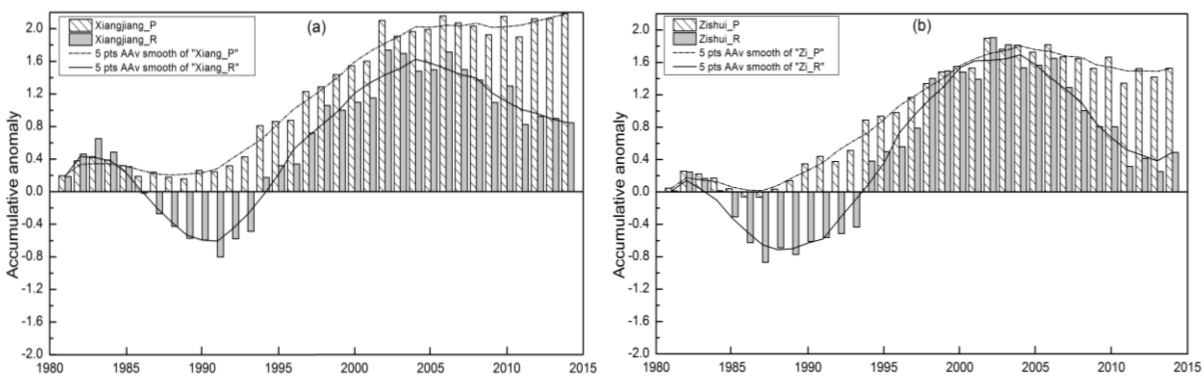
The results of Pettitt's test for change-point detection in annual precipitation, potential evapotranspiration, streamflow and temperature are given in Table 5-1. Generally, annual precipitation, potential and streamflow over most study regions display insignificant abrupt changes throughout the past entire 55 years. Specifically, abrupt changes in annual precipitation are detected in the late 1980s over the 5 study regions, although the shifts are insignificant. Regarding annual potential evapotranspiration, only 1993 is recognised by Pettitt's test as the significant change-point for Lishui, while breakpoints in the early 1970s for Xiangjiang, Zishui and Yuanjiang and 1999 for whole basin are insignificant. As for streamflow, 1983 is identified to be the significant breakpoint for Whole basin, whilst insignificant change-points in 1991 and the early 2000s are for the remaining 4 study regions. It should be noted that 1983 is the significant breakpoint for streamflow time series only for Whole basin rather than the remaining 4 study regions. This implies that streamflow in the entire basin is largely affected by the Main Lake sub-basin, where the Yangtze River contributes greatly to the Main Lake sub-basin through the Three Channels and the only outlet (Chenglingji) for the entire basin connecting the Main Lake sub-basin with the Yangtze River. The results are generally consistent with Yuan et al. (2015), where significant abrupt change in water level for the outlet of Whole basin (Chenglingji) occurs in 1980, and 2003 could be the potential abrupt point. By contrast, annual temperature over all the 5 study regions exhibits abrupt changes at the significance level of 0.05 in the 1990s, indicating significant annual temperature shifts before and after the breakpoints. The results are in correspondence with Tong Ji-Long (2014), where the significant abrupt temperature change in the Yangtze River is identified to be around 1996 by the Mann-Kendall abrupt test method.

Table 5-1 Pettitt's test for abrupt point detection during the period of 1960-2014 over the 5 study regions (* indicates significance level of 0.05)

	Xiangjiang	Zishui	Yuanjiang	Lishui	Whole basin
P	1989	1987	1989	1988	1986
Ep	1972	1972	1974	1993*	1999

R	1991	2002	2004	2003	1983*
T	1997*	1997*	1996*	1993*	1993*

The Pettitt's test results are further compared with and validated by the cumulative anomaly method, which can detect the possible change-points in a time series. Fig. 5.4 depicts the cumulative anomalies and for annual precipitation and streamflow over the 5 study regions. The graphs show that annual precipitation over the 5 regions generally decreases with negative slopes for the cumulative anomalies before the late 1980s, while increases with positive slopes after that, indicating that abrupt changes in annual precipitation might occur during the late 1980s. It can be also referred from Fig. 5.4 that the early 1980s, 1990s and 2000s could be the probable breakpoints in annual streamflow for the 5 study regions. The results from accumulative anomaly method are highly consistent with those from nonparametric Pettitt's test. Therefore, the detection results obtained by the Pettitt's method can be used for the division of analysis periods.



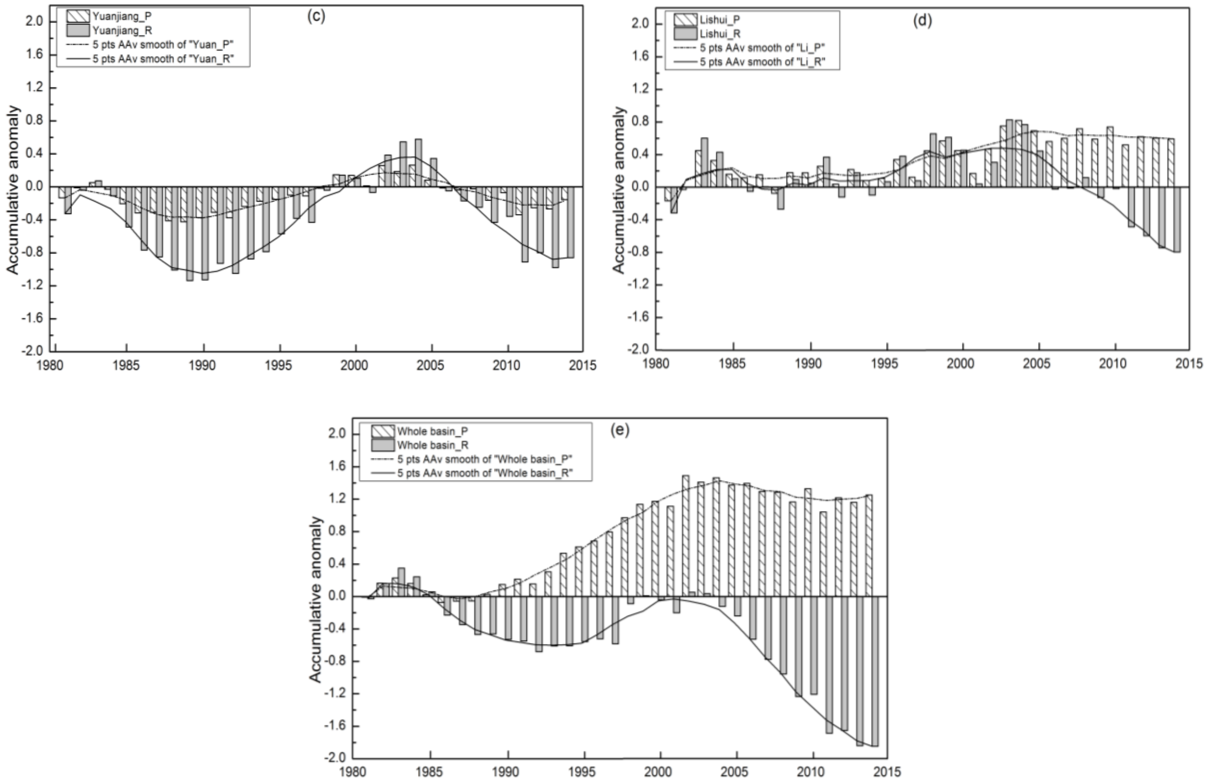


Fig. 5.4 Cumulative anomalies and the 5 pts AAV smooth results for annual precipitation (P) and runoff depth (R) over the 5 study regions during 1981-2014

According to Dai et al. (2015), scarce development occurred before 1980 over the entire Yangtze River basin. However, after 1980, human interference including hydraulic construction and water usage rapidly took place. During the period 1980-2010, annual water usage in the Yangtze Basin has increased by $100\times10^9m^3$, which has inevitably posed great pressure on water resources in Dongting basin. On the other hand, the two giant dams, Gezhouba Dam and Three Gorges Dam began to put into use in 1981 and 2003, respectively. The operation of the dams not only has reallocated inner-annual flow pattern along the Yangtze River basin, but also has modified the river-lake interaction between the Yangtze River and Dongting Lake, incurring more water supply from Dongting Lake to the Yangtze River (Dai et al., 2010). Based on the Pettitt’s test results and to address significant human activities on streamflow changes, 1981 and 2003 are selected as the division points for the whole period of 1960-2014. The early period of 1960-1980 is the benchmark period, the two periods of 1981-2002 and 2003-2014 are two impaired time intervals characterised by remarkable changes in streamflow resulting from the combined effects of climatic variation and intensive human activities. The division of the analysis periods corresponds to Yuan (Yuan et al., 2015, Yuan et al., 2016), in which the period 1960-2010 was split into three sub-periods (1960-1980, 1981-2002, 2003-2014).

Since gaps in streamflow exist among the three analysis periods, the early (1960-1980), central (1981-2002), late (2003-2014), and overall (1960-2014) periods are used for the trend analysis. Here, the Mann-Kendall trend test is used to assess the significance of trends in hydro-meteorological variables, and linear slopes are computed to further quantify the increasing or decreasing magnitudes by fitting the linear trend lines. Although annual potential evapotranspiration generally decreases with negative linear slopes over all the regions except Lishui sub-basin, no statistically significant trends are detected over all the five study regions during the four periods, as shown in Table 5-2. Also, during the pre-impaired period (1960-1980), all hydro-meteorological variables show no significant increasing or decreasing trends over all the 5 study regions. It seems streamflow changes over the 5 regions are largely contributed by climatic variables during the first impacted period (1981-2002), while are generally attributed to human impacts during the second impacted period (2003-2014). During the first impacted period, statistically significant increasing trends in annual temperature are identified over all the 5 study regions, where the rate of annual temperature change varies from 0.03 to 0.05℃ a^{-1}. Similarly, annual precipitation exhibits increasing trends with a range of 1.27 to 13.93 mm a^{-1} over all the 5 regions, of which the increasing trends are significant over Xiangjiang, Yuanjiang and Whole basin. The increased annual precipitation contributes to the increased annual streamflow over the study regions. Annual streamflow increases significantly over Xiangjiang, Zishui, and Yuanjiang, whereas decreases insignificantly over Lishui, which might result from the combined effects of less precipitation and more intensive human activities. During the second impacted period, both annual precipitation and streamflow show insignificantly decreasing trend over Lishui. For the remaining 4 study regions, annual precipitation exhibits increasing trends with a range of 8.73-12.05 mm a^{-1}, and the trend is statistically significant over Yuanjiang. By contrast, annual streamflow shows insignificant decreasing trends over Xiangjiang, Yuanjiang, and Lishui, whilst insignificant increasing trends over Zishui and Whole basin. The discrepancy between precipitation and streamflow might be attributable to changes in basin characteristics and upstream inflow from the Yangtze River, which suffers from significant human interference in recent 10 years. Overall, during the whole 55 years, except statistically significant negative trend in annual streamflow over Whole basin and significant positive trends in annual temperature over the 5 regions, no significant trends are detected in other variables over the 5 regions. Annual precipitation displays insignificant increasing trends ranging from 0.69 to 2.02 mm a^{-1} over all 5 regions. Corresponding to the changing trends in precipitation, Xiangjiang and Zishui show slightly yet insignificantly increasing trends in streamflow, while Yuanjiang, Lishui and Whole basin exhibit opposite changing trends in streamflow, indicating that other factors except for precipitation result in changes in streamflow over the 3 study regions. The conclusion of increasing trend in temperature over the 5 study regions is consistent with the study by Sang et al. (2013), who concluded that temperature in Dongting Lake Basin showed an upward trend after the 1980s based on the long-term (1961-2010) observed temperature dataset obtained from the same data source of this study. According to Qu et al. (2016), the annual precipitation exhibited insignificant increasing trends for 1960-2013 over Dongting Lake basin, which agrees well with the results of this study.

Table 5-2 Mann-Kendall (MK) trend test at significance levels of 0.05, 0.01, and 0.1 (NS indicates significance level exceeds 0.1) and linear slopes (mm a^{-1} or ℃ a^{-1}) in annual precipitation, potential evapotranspiration, temperature and runoff depth over the 5 study regions

	Study region	1960-1980		1981-2002		2003-2014		1960-2014	
		MK test	Slope	MK test	Slope	MK test	Slope	MK test	Slope
P	Xiangjiang	NS	0.64	0.1	13.93	NS	12.05	NS	2.02
	Zishui	NS	0.06	NS	11.79	NS	9.05	NS	0.91
	Yuanjiang	NS	5.07	0.1	8.91	0.05	11.03	NS	0.24
	Lishui	NS	-5.88	NS	1.27	NS	-12.94	NS	0.69
	Whole basin	NS	2.29	0.1	11.22	NS	8.73	NS	1.09
Ep	Xiangjiang	NS	-1.78	NS	-0.70	NS	-3.32	NS	-0.07
	Zishui	NS	-1.21	NS	-0.83	NS	-2.97	NS	-0.45
	Yuanjiang	NS	-1.67	NS	-0.70	NS	-1.53	NS	-0.34
	Lishui	NS	0.767	NS	-0.652	NS	0.36	NS	0.97
	Whole basin	NS	-1.02	NS	-0.71	NS	-2.60	NS	-0.34
T	Xiangjiang	NS	-0.01	0.05	0.03	NS	-0.01	0.01	0.02
	Zishui	NS	-0.01	0.05	0.03	NS	-0.01	0.01	0.02
	Yuanjiang	NS	-0.01	0.05	0.03	NS	-0.02	0.01	0.01
	Lishui	NS	-0.01	0.01	0.05	NS	-0.02	0.01	0.02
	Whole basin	NS	-0.01	0.01	0.05	NS	-0.02	0.01	0.02
R	Xiangjiang	NS	1.23	0.1	11.16	NS	-0.41	NS	0.93
	Zishui	NS	0.82	0.1	11.54	NS	7.21	NS	0.26
	Yuanjiang	NS	4.27	0.05	9.11	NS	-0.54	NS	-0.76
	Lishui	NS	-1.58	NS	-0.05	NS	-16.01	NS	-2.33
	Whole basin	NS	-12.48	NS	6.88	NS	2.29	-0.01	-5.31

5.3.3 Streamflow sensitivity to climate changes and human contributions

For the four sub-basins, Xiangjiang, Zishi, Yuanjiang, and Lishui, there is no other source of inflow. Therefore, for the water balance equation (Q = P-E-ΔS), Q is the runoff depth converted from the observed runoff at the respective controlling gauging stations (Xiangtan, Taojiang, Taoyuan, and Shimen) over the four sub-basins (Fig. 3.1(a)). It should be noted that for the Whole basin, there are inflows from Yangtze River basin through the Three Channels (Songzikou, Taipingkou, Ouchikou) to the main Dongting Lake (Fig. 3.1). Therefore, when applying the water balance equation, Q should be the runoff depth difference between the runoff at Chenglingji station (outflow controlling gauging station for the Whole basin) and the total runoff at Three Channels flowing into the Whole basin. Details of data information can be found in data sources section.

The annual climatic dryness index (Ep/P) and the evapotranspiration ratio (E/P) are used to derive *w* parameter of the Budyko curve by fitting Fu's equation ($\frac{E}{P} = 1 + \frac{E_p}{P} - \left[1 + \left(\frac{E_p}{P}\right)^w\right]^{\frac{1}{w}}$) for each study region during each analysis period (Table 5-3 and Fig. 5.5). It can be seen that for each analysis period, there is limited variability in *w* parameters among the 5 study regions, indicating that the combined effects of each sub-basin characteristics on water balance are very similar. Besides, the *w* parameter over each sub-basin generally increases slightly after the pre-change period (1960-1980), which leads to an upward shift of the Budyko curve (Fig. 5.5). As a result, the actual evapotranspiration increases under the same precipitation and potential evapotranspiration, thus yielding decreased streamflow. Specifically, *w* parameters over Xiangjiang and Zishui show similar changing pattern with an increase from the pre-change period to the first-impacted period and a decrease during the second-impacted period, and *w* parameters over the remaining three study regions show similar changing pattern with an increase from the pre-change period to the first-impacted period and a further increase during the second-impacted period. This can be easily seen from Fig. 5.5, the Budyko curve of the pre-change period is below those of the two impacted periods over each of the five study regions. The Budyko curve of the first-impacted period is higher than that of the second-impacted period over Xiangjiang and Zishui, while lower over the remaining three study regions. In Fig. 5.5, it also illustrates the points (E_p/P, E/P) of the average values during different periods. The locations of the points show similar patterns over all the five study regions, with A at the bottom, B at the up left and C at the up right side of A.

Table 5-3 The parameter *w* for the 5 study regions over 3 periods

Period	Xiangjiang	Zishui	Yuanjiang	Lishui	Whole basin
1960-1980	1.76	1.68	1.73	1.58	1.64
1981-2002	1.84	1.76	1.79	1.69	1.76
2003-2014	1.77	1.73	1.86	1.92	1.84

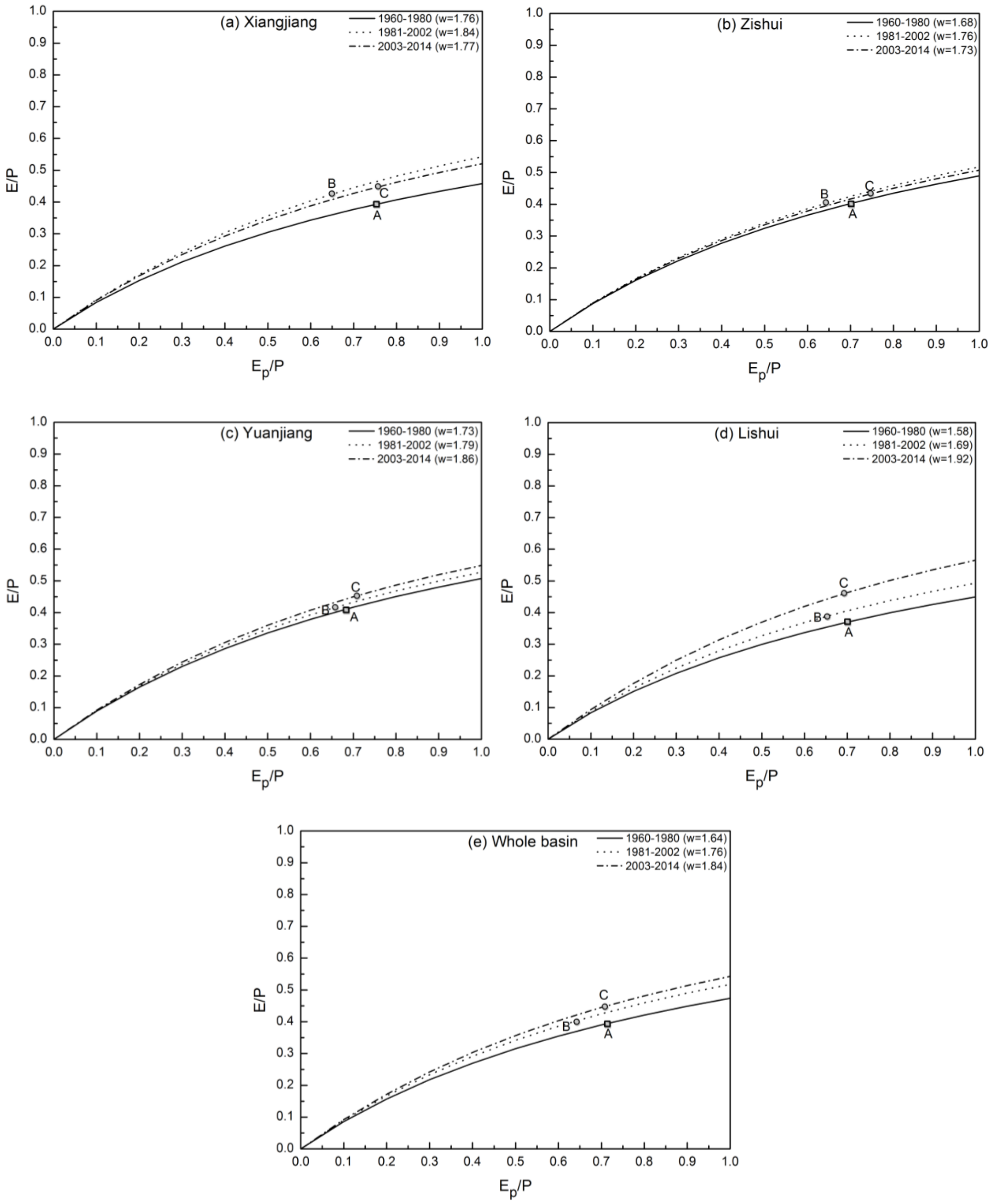


Fig. 5.5 Budyko curves for the 5 study regions over 3 periods (A, B, C represent the points (E_p/P, E/P) of the average values during the pre-change period (1960-1980), the first-impacted period (1981-2002) and the second-impacted period (2003-2014))

Based on the two Budyko-based decomposition and elasticity methods, the calculated *w* parameters for the pre-change period (1960-1980) are used to estimate relative changes in annual streamflow due to climate and human impacts. It can be seen from Table 5-4 that during the first-impacted period, there are increases in annual streamflow with a range of 28~69mm over Xiangjiang, Zishui, Yuanjiang and the Whole basin, while a slightly decrease of 16mm in Lishui. During the second-impacted period, annual streamflow over all the five study regions decreases with a range of 18~117mm. As listed in Table 5-4, the results from the two Budyko-based methods are highly identical, and both climate and human activities are the driving factors that changed the streamflow. Human activities have induced a decrease in streamflow over all the five study regions during the two impacted periods. Climate change or variability have contributed an increase in streamflow over all the five study regions except for Lishui region during the first-impacted period, while a decrease over all the five study regions during the second-impacted period. It can be seen from Table 5-4 that the relative effects of climatic factor and human impact vary among the five study regions during the two impacted periods. However, climatic factor has played a dominant role in changing annual streamflow during the first-impacted period, while human impact has become the major driving factor for the decrease of annual streamflow during the second-impacted period.

Table 5-4 Impacts of climate and human activities on annual streamflow change

Study region	Period	ΔQ^T (mm)	Decomposition method				Elasticity method			
			ΔQ^c (mm)	ΔQ^h (mm)	$\Delta Q^c/\Delta Q^T$ (%)	$\Delta Q^h/\Delta Q^T$ (%)	ΔQ^c (mm)	ΔQ^h (mm)	$\Delta Q^c/\Delta Q^T$ (%)	$\Delta Q^h/\Delta Q^T$ (%)
Xiangjiang	Period 2	69	112	-43	162.3	-62.3	111	-42	160.9	-60.9
	Period 3	-18	-5	-13	27.8	72.2	-3	-15	16.7	83.3

Zishui	Period 2	54	96	-42	177.8	-77.8	91	-37	168.5	-68.5
	Period 3	-47	-17	-30	36.2	63.8	-19	-28	40.4	59.6
Yuanjiang	Period 2	30	70	-40	233.3	-133.3	68	-38	226.7	-126.7
	Period 3	-85	-34	-51	40.0	60.0	-31	-54	36.5	63.5
Lishui	Period 2	-16	-10	-6	62.5	37.5	-11	-5	68.8	31.3
	Period 3	-117	-50	-67	42.7	57.3	-46	-71	39.3	60.7
Whole basin	Period 2	28	88	-60	314.3	-214.3	84	-56	300.0	-200.0
	Period 3	-76	-29	-47	38.2	61.8	-31	-45	40.8	59.2

Since the two Budyko-based methods yield close results, the following analysis is mainly focused on the results from decomposition method. Table 5-5 gives the contribution of climatic factor and human activities to annual streamflow changes compared to the benchmark period of 1960-1980. According to Table 5-4 and Table 5-5, from the benchmark period to the first-impacted period, climatic factor plays a crucial role in increasing streamflow over Xiangjiang, Zishui,Yuangjiang, and the Whole basin. Increases in annual streamflow induced by climatic factor range from 70~112mm in the first-impacted period, accounting for 59.5%~72.3% of the annual streamflow changes. However, Lishui has seen a decrease of 10mm in annual streamflow induced by climatic factor, which contributes 62.5% of the annual streamflow change. Human-induced changes in annual streamflow account for 27.7%~40.5% over the five study regions. Among the five study regions, Xiangjiang experiences the greatest increase in annual streamflow with an average of 69mm during the first-impacted period, of which climatic factor contributes to an increase of 112cm while human activities contribute to a decrease of 43mm. The Whole basin has the least increase in annual streamflow with an average of 28mm, of which climate-induced and human-induced changes account for 59.5% and 40.5%, respectively.

From the benchmark period to the second-impacted period, both climate effect and human activities have induced decreases in streamflow over the five study regions (the result from elasticity method for the Whole basin also has the same conclusion), and human activities on streamflow are the critical reason for the overall reduced streamflow. Human-induced changes in annual streamflow contribute for 57.3%~72.2% of the total decreases in annual streamflow. Streamflow in Lishui experiences the most significant decrease, and followed by Yuanjiang and the Whole basin. In Lishui sub-basin, there is a substantial decrease in streamflow with an average of 117mm, of which climate-induced and human-induced decreases account for 42.7% and 57.3% of the total decrease of the annual streamflow, respectively. Streamflow in Xiangjiang has the least decrease with an average of 18mm, of which climate and human impacts account for 27.8% and 72.2% of the total reduced annual streamflow, respectively.

Table 5-5 Contribution of climatic factor and human activities on the change of annual streamflow compared to the benchmark period 1960–1980.

Study region	Period	Q_T (mm)	ΔQ^T (mm)	Contribution of climatic factor		Contribution of human activities	
				ΔQ^c (mm)	η_c (%)	ΔQ^h (mm)	η_h (%)
Xiangjiang	Period 1	795	NA	NA	NA	NA	NA
	Period 2	864	69	112	72.3	-43.0	27.7
	Period 3	777	-18	-5	27.8	-13.0	72.2
Zishui	Period 1	849	NA	NA	NA	NA	NA
	Period 2	903	54	96	69.6	-42.0	30.4
	Period 3	802	-47	-17	36.2	-30.0	63.8
Yuanjiang	Period 1	852	NA	NA	NA	NA	NA
	Period 2	882	30	70	63.6	-40.0	36.4
	Period 3	767	-85	-34	40.0	-51.0	60.0
Lishui	Period 1	943	NA	NA	NA	NA	NA
	Period 2	927	-16	-10	62.5	-6.0	37.5
	Period 3	826	-117	-50	42.7	-67.0	57.3
Whole basin	Period 1	852	NA	NA	NA	NA	NA
	Period 2	880	28	88	59.5	-60.0	40.5
	Period 3	776	-76	-29	38.2	-47.0	61.8

The decreased streamflow by human activities can be confirmed by intensive human activities. As discussed in chapter 4, in the recent 55 years, rapid economic development and population growth have exerted intense pressure on the water resources within Dongting Lake basin. According to (Dai et al. (2015)), the Yangtze River basin is weakly regulated during the pre-change period, while intermediately regulated between 1980 and 2010, and is highly regulated at present. There is an increase in water usage of 100×10^9 m^3 a^{-1} in the Yangtze River basin during the period of 1980-2010 resulted from the rapid and huge economic development. In 1990, the annual total usage is equivalent to 15% of the runoff, and it is almost 25% in 2010.

Currently, there exists only one study conducted by Yuan et al. (2016) to quantitatively distinguish the contribution of climate and human factors to streamflow in Dongting Lake. They also applied the Budyko framework to assess the impacts of climate and human impacts on streamflow in the main lake region rather than the whole Dongting Lake basin during the same analysis periods as this study. In their work, meteorological data from Changde, Yuangjiang and Yueyang meteorological stations were used to represent the west, south and east parts of the main lake region (Fig. 5.5). However, it can be seen from Fig. 5.5 that Changde meteorological station is located in the Yuanjiang sub-region, and Yuangjiang and Yueyang meteorological stations are sited near the outlet of the Zishui sub-region and the Whole basin, respectively. Therefore, the results for west, south and east parts of the main lake region in Yuan et al. (2016) can be compared with the results for Yuanjiang, Zishui and the Whole basin in this study, respectively. During the first-impacted period, climate-induced streamflow changes contribute 43.20%, 67.27% and 60.07% to the streamflow alterations over west, south and east parts of the main lake region in Yuan et al. (2016), respectively. In this study, climate-induced changes contribute 63.6%, 69.6% and 59.5% to the streamflow alterations over Yuanjiang, Zishui and the Whole basin, respectively. Except for discrepancy between west part of the main lake region, the remaining results agree well between Yuan et al. (2016) and this study. During the second-impacted period, climate-induced streamflow changes contribute 38.38%, 21.67% and 41.11% to the streamflow alterations over west, south and east parts of the main lake region in Yuan et al. (2016), respectively. In this study, climate-induced changes contribute 40.0%, 36.2% and 38.2% to the streamflow alterations over Yuanjiang, Zishui and the Whole basin, respectively. The results for west and east parts of the main lake from Yuan et al. (2016) are comparable well with the result for Yuanjiang and the Whole basin in this study, yet there exists some difference between the south part of the main lake in Yuan et al. (2016) and Zishui in this study. Overall, both Yuan et al. (2016) and this study show the same conclusion that both climatic factor and human activities contribute to changes in streamflow during the two impacted periods, and climatic factor overweighs human activities during the first-impacted period while human activities become the most decisive driving factor during the second-impacted period.

By comparison with other studies on similar locations as Dongting Lake, the results of this study exist within a reasonably consistent range. According to Wang et al. (2013b), who investigated the impacts of climate and human activities on streamflow in the Yangtze River basin, and concluded that the impact of human activities exceeded the impact of climate factor and was responsible for 71% of the changes in streamflow in the whole Yangtze River basin during the period of 1970-2008. Climate factor contributed to 74% and 43% of the changes in streamflow at Yichang and Hankou stations, of which Yichang station is upstream of Dongting Lake basin and Hankou station is downstream of Dongting Lake basin. Zhang et al. (2016b) evaluated the impacts of climate change and human activities on streamflow in

Poyang Lake basin, which is adjacent to Dongting basin and has similar hydrological and meteorological condition as Dongting Lake basin. The contributions of human activities and climate change to streamflow changes were 73.2% and 26.8% over Poyang Lake basin during the period of 1970-2009, respectively.

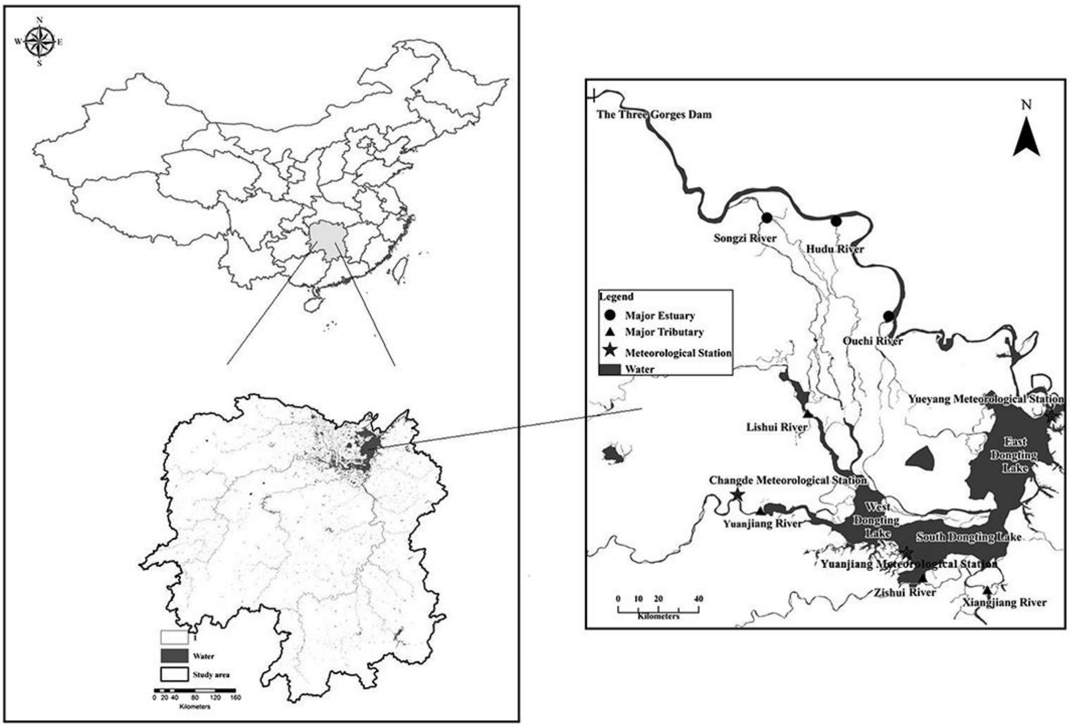


Fig. 5.5 Budyko curves for the 5 study regions over 3 periods (A, B, C represent the points (E_p/P, E/P) of the average values during the pre-change period (1960-1980), the first-impacted period (1981-2002) and the second-impacted period (2003-2014))

The Budyko-based decomposition and runoff sensitivity methods make it possible to easily quantitatively assessing the respective effects of climate change (variability) and human activities on runoff. However, uncertainty may arise from the limited hydro-meteorological observation data. There is no complete meteorological data in several meteorological stations, so observed data from the nearby stations are used, which may restrict the accuracy of the calculated PET and simulated runoff.

5.4 Conclusions

In this chapter, the roles of climate and human impacts on streamflow over the five study regions are investigated based on the long-term hydrological and meteorological data using the Budyko-based methods over the two impacted periods. The long-term hydro-meteorological characteristics over the four sub-basins (Xiangjiang, Zishui, Yuanjiang, and Lishui) and the entire Dongting Lake basin are examined. The long-term average (1960-2014) hydro-climatology varies slightly over the 5 study regions. For example, the maximum difference in annual runoff depth exists between Lishui and Yuanjiang, with the former 177 mm yr^{-1} higher than the latter. For the same time and study region, although annual precipitation and annual runoff depth have the same direction of departure of annual value from the long-term average, annual runoff depth shows more intensive changes with higher anomalies.

To characterize the temperal varaitions of hydro-climatology over the five study regions, the abrupt change of the hydro-climatology is detected by the Pettitt's test for change-point detection and the changing trend is identified by the Mann-Kendall (MK) trend test. Considering the Pettitt's test results and obvious human activities on streamflow changes, 1981 and 2003 are selected as the division points of the whole period of 1960-2014 to spatially identify the un-impacted period and impacted periods. According to the results from the MK trend test, hydro-climatology shows slightly different variations over the five study regions, but no significant changing trend was detected during the benchmark period. During the first-impacted period, there are significant increasing trends in precipitation over Xiangjiang, Yuanjiang and the Whole basin, runoff depth over Xiangjiang, Zishui and Yuanjiang, and temperature over all five study regions. During the second-impacted period, only precipitation over Yuanjiang shows significant increasing trend, while no significant trend is detected for the remaining hydrological and meteorological variables.

The Budyko-based decomposition and runoff sensitivity methods are used to quantitatively assess the respective impact of climatic variations and human activities on streamflow alteration over the five study regions. The two methods yield highly close results that both climate and human activities are the driving factors that change the streamflow. During the first-impacted period, climatic factor is a crucial role in changing annual streamflow over all the five study regions, accounting for 59.5%~72.3% of the total changes in annual streamflow. Annual streamflow over Xiangjiang, Zishui, Yuanjiang and the Whole basin increase to various extents with a range of 28~69mm, of which climatic factor and human impact contribute to 56.8%~72.3% and 27.7%~40.5%, respectively. While streamflow over Lishui decrease slightly, of which climatic factor accounts for 62.5%. During the second-impacted period, streamflow over all the five study regions decrease resulted from both climate and human impacts, with more outstanding impact from human activities. Human-induced and climate-induced changes in annual streamflow contribute to 57.3%~72.2% and 27.8%~42.7% of the overall changes in annual streamflow, respectively. During the two impacted periods, human activities have reduced streamflow over all five study regions. During the first-impacted period, climate change or variability has increased streamflow over all the five study regions except for Lishui, while a decrease over Xiangjiang, Zishui and Yuanjiang during the second-impacted period.

6 CONCLUSIONS

6.1 Introduction

This thesis has presented a systematic study into the flow regime alterations in Dongting Lake and the impacts of climate and human activities. A large amount of analytical work has been presented in this thesis, which mainly aimed to investigate the following aspects: (1) to investigate the observed historical climate and hydrological conditions in Dongting Lake and to characterize the natural flow regimes during the un-impacted period; (2) to quantify the full ranges of flow regime changes in Dongting Lake with the hydrologic metrics of indicators of hydrologic alteration (IHA) during the two impacted periods; (3) to distinguish the respective impacts of climate variabilities and human activities on streamflow using the Budyko-based decomposition and runoff sensitivity methods.

6.2 Conclusions

In this thesis, a detailed description about the geographic location, climate and hydrological conditions, land use and human activities over the Dongting Lake, as well as the data sources used in this thesis are given. Affected by subtropical monsoon climate, both precipitation and streamflow exhibits remarkable seasonal variations. Over half of the annual precipitation occurs during the flood season from April to August, corresponding to high discharge during the same period. The runoff rhythms of Three Channels and Four Rivers are not synchronous. Four Rivers serve as the dominant inflow sources for the lake before June, while hereafter Three Channels and Four Rivers play almost equivalent roles in supplying water for lake area. The land use/cover types are significantly affected by the regional economic development. The lake suffers from extensive impoldering and long-term siltation in the past several decades, which cause severe degradation of the lake. Besides, upstream human activities, especially the regulation of TGD and GD, may largely affect the natural hydrologic regimes in Dongting Lake.

The observed natural streamflow during the pre-impacted period as well as streamflow changes during the two post-impacted periods are analysed. Moreover, the natural flow regimes and hydrologic shifts in the pattern, magnitude, timing, duration and direction of lake flow are investigated on annual, quarterly, monthly, weekly and daily scales, based on the hydrologic metrics of indicators of hydrologic alteration (IHA). Results show that flow regimes in Dongting Lake have been largely altered following TGD regulation under the four dam operational modes. Flow duration curves and the relationships between water level and discharge have also been altered following TGD operation under all operational modes. Furthermore, the hydrologic alterations of Dongting Lake are fully characterized using a set of hydrologic metrics to investigate the pre- and post-dam hydrologic changes in flow magnitude, frequency, duration, timing and rate of change during the three analysis periods. The analytical results show that the annual flows are noticeably lower in post-dam periods, and monthly flows are also reduced except from January to March, when monthly flows were marginally augmented. Slight increases in the 1 through 90 day minimum flows and significant decreases in the 1 through 90 day maximum flows are detected, along with increasing changing magnitude corresponding to increasing duration. Also, the timing of annual extreme low flow is marginally altered while not obviously changed for extreme high flow. Other significant alterations include changes in the number and duration of high and low pulses, lower rate of hydrograph rise and fall, and a higher number of hydrograph reversals. All the flow metrics exhibit similar variabilities during the two post-dam periods, and the alterations are more severe following the impoundment of Three Gorges Dam.

In the last part of this thesis, the relative changes in climatic variations and human activities on streamflow over the four sub-basins as well as the whole Dongting Lake are investigated. Concerning the Pettitt's test results and obvious human activities on streamflow changes, 1981 and 2003 are selected as the division points of the whole period of 1960-2014 to spatially identify the un-impacted period and impacted periods. According to the results from the MK trend test, there exist significant increasing trends in precipitation over Xiangjiang, Yuanjiang and the Whole basin, runoff depth over Xiangjiang, Zishui and Yuanjiang, and temperature over all five study regions during the first-impacted period, and significant increasing trend in precipitation over Yuanjiang during the second-impacted period. The impacts of climate variations and human activities on streamflow are examined by the Budyko-based decomposition and runoff elasticity methods. The two methods yield very similar results with the conclusion that both climate and human activities are the driving factors that change the streamflow. During the first-impacted period, streamflow over Xiangjiang, Zishui, Yuanjiang and the Whole basin increase to various extents with climatic factor being a crucial role, while streamflow over Lishui decrease slightly with human activities being a decisive role. Over the five study regions, climatic factor accounts for 59.5%~72.3% of the total changes in annual streamflow, while human activities contribute 27.7%~40.5%. During the second-impacted period, streamflow over all five regions show a decrease resulted from both climate and human impacts, with more outstanding impact from human activities. Human-induced change in annual streamflow over the five study ranges from 57.3% to 72.2 of the total changes in annual streamflow, while climate-induced change varies between 27.8% and 42.7% over the five study regions. During the two impacted periods, human activities have reduced streamflow over all five study regions. During the first-impacted period, climate change or variability have increased streamflow over all the five study regions, while a decrease over Xiangjiang, Zishui and Yuanjiang during the second-impacted period.

6.3 Future research

This thesis has presented a systematic study on the flow regime changes in Dongting Lake and has quantified the relative effects of climate and human activities. It provides a good understanding of the flow characteristic of Dongting Lake under changing climate and human interventions. More research studies, however, are still needed to be conducted in the future. Some of the issues that need further research are detailed below:

The availability of observed data is always a big concern in the field of hydrology and meteorology. In this thesis, the post-TGD data adopted were only for 12 years (2003-2014). As it is preferable to use over 15 years of post-dam data in applying IHA to quantify the full ranges of hydrological changes, study should continue after the availability of more observed data. Also, when using the budyko-based methods to distinguish the impacts of climate change (variability) from human activities on streamflow, uncertainty may arise from the limited hydro-meteorological observation data. There was no complete meteorological data in several meteorological stations, so observed data from the nearby stations were used, which might restrict the accuracy of the calculated PET and simulated runoff.

This thesis restricts the research to the quantitative assessment of the contributions of climate variations and human activities to the changes in runoff, the reason why and how climate variations and human activities had changed the flow regimes in Dongting Lake, and why it showed spatial discrepancy in the flow regime changes over the five study regions still need further exploration.

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