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Forest recovery and river discharge at the regional scale of Guangdong Province, China

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[1] Information on how large-scale forest changes affect water resources is important in China as country-wide reforestation programs are being implemented and concerns have arisen over possible water reduction. In this study, water budget analysis and statistical methods were used to assess the effects of significant forest recovery on river discharge at Guangdong Province based on 50 years of data. We used realized water yield (RWY) as a balance term between the outflows from and inflows to the province to represent the river discharge produced solely in Guangdong Province. The relationship between forest recovery and RWY was inferred after quantitatively examining other contributing variables including precipitation, potential evapotranspiration, development of impervious areas, human water consumption, and reservoir constructions. We applied time series analysis to test the statistical relationship between forest recovery and RWYs at annual, wet season, and dry season intervals. Both approaches showed that large-scale forest recovery did not cause significant water reduction over the past 50 years. This finding is contrary to the widely held perception of the trade-off relationship between carbon (reforestation) and water. There were no significant trends in precipitation or in RWY annually and in the wet season, but there was a significant increase of RWY in the dry season over the past 50 years. It is estimated that forest recovery may play a positive role in redistributing water from the wet season to the dry season and, consequently, in increasing water yield in the dry season. The implication of those research findings for future reforestation programs and water resource protection is also discussed.

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1. Introduction

[2] The relationship between forest changes and river discharge has long been an important research topic [*Scott and Prinsloo*, 2008; *McVicar et al.*, 2007a; *Lin and Wei*, 2008]. Over the past 100 years, this topic has been intensively studied using paired watershed experiments. Several review papers have been published that summarize the relationship between forest changes and streamflows [e.g., *Bosch and Hewlett*, 1982; *Bruijnzeel*, 2004; *Wei et al.*, 2008]. The general conclusion is that forest removal or harvesting increases streamflow, whereas reforestation causes its reduction. But the amount of this reduction is highly variable from one experiment to another [*Bruijnzeel*, 2004], which implies complicated interactions among vegetation, climate, and soil. The reduction in streamflow due to reforestation is further summarized by the trade-off between forests and water [*Jackson et al.*, 2005; *Sun et al.*, 2006]. However, this general conclusion is based on small-scale paired watershed studies [*Bradshaw et al.*, 2007; *Oudin et al.*, 2008]. Furthermore, other research has demonstrated that the results from small-scale watersheds cannot be easily extrapolated to large-scale watersheds [*Albert and Keenan*, 2007].

[3] Research on the relationship between forest changes and river discharge in large-scale watersheds (e.g., >1000 km^2) is rare mainly because of the difficulty in locating a similar watershed as a control [*Costa et al.*, 2003; *Siriwardena et al.*, 2006]. In addition, the results for large-scale watersheds are inconsistent. For example, *Costa et al.* [2003] studied the discharge changes in an upstream basin of the Tocantins River, in southeastern Amazonia, which has a drainage area of 175,360 km^2. The annual mean discharge was significantly enhanced after 19% of the forest land was transformed into cropland and pasture use. *Lin and Wei* [2008] studied the impact of forest harvesting on hydrology for a large-scale forested watershed and concluded that forest harvesting significantly increased mean and peak flows over annual and spring periods. In contrast, some studies found limited [*Buttle and Metcalfe*, 2000] or no responses [*Wei and Davidson*, 1998; *Dyhr-Nielsen*, 1986; *Wilk et al.*, 2001; *Antonio et al.*, 2008]. The difficulty of extrapolating the results from different spatial scales, together

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with existing inconsistent results and, more importantly, significant lack of large-scale watershed studies clearly highlights a critical need to assess the forests and water relationships at large spatial scales. Such a need is further exemplified in the requirement for more information when dealing with global climate change and large-scale forest disturbance issues.

[4] A large-scale flood occurred in the Yangtze River basin in 1998. The flood killed more than 2000 people and caused a direct loss of about 264 billion Chinese RMB (equivalent US$33 billion). The tragedy acted as a wake-up call to China to recognize the importance of forest protection. Since then, China has increased its reforestation campaign by implementing several large-scale reforestation and protection programs. Successful implementation of these programs has changed the forest cover in China from 16.0% in the 1980s to 20.6% in 2009. It is expected that the forest cover will be continuously increasing as China plans to grow more trees (e.g., 40 million ha by 2020) to store more carbon and protect the environment. However, a growing concern has been expressed over water or streamflow reduction as a result of the large-scale reforestation effort, particularly in the drier northern and western regions of China where water is an ultimate controlling factor for regional development [*Laurance*, 2007; *McVicar et al.*, 2007b; *Guo et al.*, 2008; *Wei et al.*, 2008]. In the Guangdong Province of China, reforestation efforts have dramatically increased the forest cover from approximately 20% in the 1950s to approximately 60% at present [*Zhou et al.*, 2008]. Understanding the impacts of such a dramatic increase in forest cover on river discharge is a critical research and management question for Guangdong Province.

[5] Research on the evaluation of the relationship between forest cover and water yield in large-scale watersheds is challenging mainly due to the lack of commonly accepted research methods [*Wei and Zhang*, 2010]. Because of the difficulty of applying the insights from paired watershed experiments, suitable for small-scale (e.g., <10 km^2) to large-scale watersheds (e.g., >1000 km^2), researchers generally take either modeling or statistical approaches to study the forest-water relationship at large-scale watersheds. The modeling approach [*Sun et al.*, 2006; *Guo et al.*, 2008] is useful and effective, but it is often constrained by a lack of data and empirical equations in describing various landscape components (e.g., forests, ponds, wetlands, lakes, and stream networks) and their complicated interactions. The statistical approaches such as nonparametric tests and time series analysis can be used to directly test the significant relationship between dependent and independent variables, but it may not lead to understanding the underlying mechanisms of the studied relations.

[6] In this study, we adopted a water budget approach in combination with statistical approaches to evaluate the impacts of forest recovery on river discharge at the regional scale of Guangdong Province, China. The statistical method is used to test the relationship between forest recovery and river discharge, whereas the water budget method is used for quantifying the relative role of forests in influencing river discharge, among many other variables. Our research objectives of this paper are as follows: (1) to quantify the long-term trends in river discharge and precipitation at the whole province scale and (2) to assess if forest recovery has caused a significant reduction of river discharge in Guangdong Province.

2. Materials and Method

2.1. Description of the Study Region

[7] Guangdong Province, with an area of 179,752 km^2, is located in southern China (20°14′–N25°31′N, 109°40′–117°20′E) (Figure 1). The Tropic of Cancer crosses the middle of the province. The altitude changes from 800 to 1000 m above sea level (asl) in the north to 0 m asl in the south, with the highest mountain being 1902 m asl. Four main rivers, the Xijiang River, Beijiang River, Dongjiang River, and Hanjiang River (Figure 1), carry the majority of the river discharge; three of them (Xijiang, Beijiang, and Dongjiang) converge into Pearl River and eventually flow through the Pearl River delta into the South China Sea (Figure 1).

[8] The climate of Guangdong Province is tropical and subtropical monsoon and is divided into wet (April to September) and dry (October to March) seasons. The annual mean temperature is 22°C. Annual precipitation amounts to 1770 mm, of which 1384 mm (78%) and 386 mm (22%) fall in the wet and dry seasons, respectively (Figure 2).

2.2. Forest Coverage Data

[9] Forest is defined as the land with foliage vertical projective cover per unit land area (FVPCPULA) larger than 20%. The minimum land area is 100 m^2. Scattered trees and patches of land with area less than 100 m^2 are not treated as "forests" even if the FVPCPULA of these lands is larger than 20%. Three approaches were adopted to determine the total forested land area of the province. The first approach is made through statistical reports by all counties within the province. The second is the forest survey conducted by the forest administration agency. In this approach, the province was arbitrarily divided into about 4000 grids, with the area of each grid being 6 × 8 km^2. A 100 m^2 sample site in each grid was randomly selected and surveyed. The third approach involves the analysis of marine satellites (in 1979) and TM (Thematic Mapper) (1986 hereafter) images. The forest coverage percentage is the summation of all forested land areas divided by the total land area of the province. Data on forest coverage were obtained from Guangdong Provincial Forest and Land Resources Bureaus. It is estimated that the error of the forest coverage in Guangdong Province is less than 1% [*State Forestry Administration*, 2006]. Missing data in the 11 years of 1961–1962, 1965, 1967, 1972, 1974, 1976–1977, 1981–1982, and 1984 were estimated using simple linear interpolations. The error associated with this estimation technique is likely minor because the forest coverage in these periods was stable. Forest cover was 20.2%–27% from 1956 to 1986, and then jumped from 38% to 54.7% between 1987 and 1994 because of the implementation of a large-scale reforestation program in Guangdong Province. The reforestation campaign was conducted entirely on uncultivated lands, shrub and herbal lands, and mine tailing lands. Since 1996, the forest cover of Guangdong Province was kept relatively stable (56.3%–55.9%).

2.3. Hydrological Data and Water Budget Analysis

[10] The data that follow are converted to units of depth (mm) over the whole province for comparative purposes. In

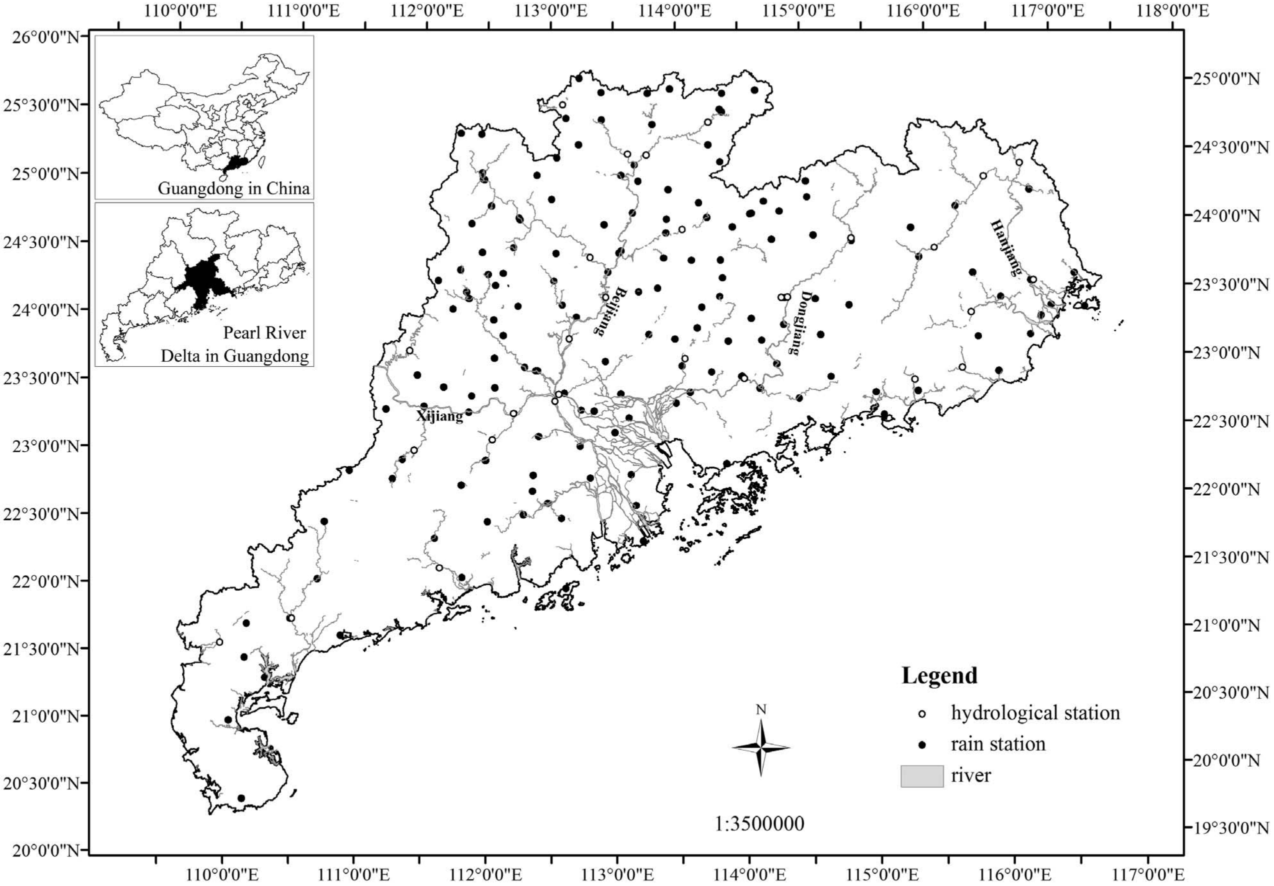

Figure 1. Spatial distribution of meteorological and hydrometric stations in Guangdong Province.

addition, precipitation and the selected hydrological variables are separated into different study periods: 1956–1961, 1962–1986, 1987–1994, and 1995–2006. Such a separation is based on differences in forest cover and construction of reservoir systems. Period 1 (1955–1961) was characterized by low reservoir capacity and low forest cover, period 2 (1962–1986) had high reservoir capacity and low forest cover, period 3 (1987–1994) had high reservoir capacity and transitional forest cover, and period 4 (1995–2006) had high reservoir capacity and high forest coverage.

2.3.1. Determination of Runoff Coefficient in Impervious Surface

[11] Three to five patches of impervious surface in each of main cities in Guangdong Province are laterally sealed to measure the runoff caused by precipitation. The area of each patch is about 1–3 ha in which as many impervious surface types as possible are included (e.g., road, house, and parking

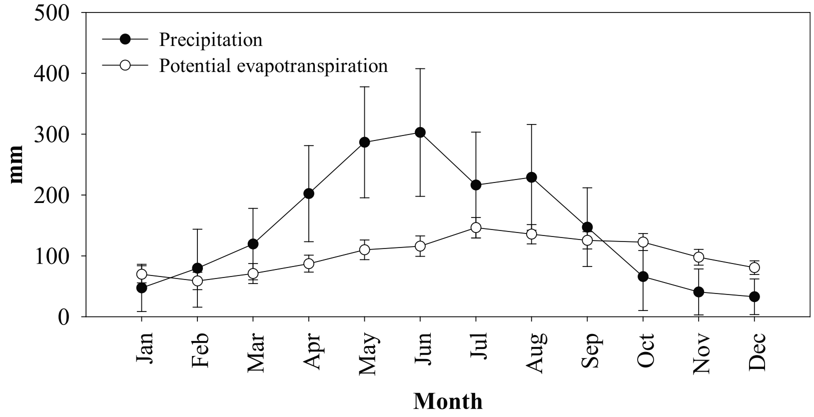

Figure 2. Monthly mean precipitation and potential evapotranspiration in Guangdong Province during the period 1956–2006.

lot). The runoff coefficient is calculated based on measured runoff and precipitation.

2.3.2. Precipitation

[12] There are 179 meteorological stations within Guangdong Province (Figure 1) that were selected to calculate average monthly, seasonal (wet and dry seasons), and annual precipitation. For the 51 years (1956–2006) of records, no daily data longer than 3 consecutive days were missed over the periods. Missing daily data were estimated by linear regression based on precipitation at neighboring stations when the correlation coefficients were greater than 0.85. Data on monthly precipitation are shown in Figure 2. The intra-annual variation of precipitation (CV_p) is estimated using the following equation:

$$\mathrm{CV}_p = \mathrm{SD}/\text{annual precipitation}, \tag{1}$$

where SD is the standard deviation of monthly precipitation.

[13] Parallel to the 179 meteorological stations belonging to the Guangdong Provincial Hydrological Bureau (GPHB), there are another 86 meteorological stations belonging to Guangdong Provincial Meteorological Bureau (GPMB). The precipitation from GPMB was taken as a comparison with the precipitation from GPHB before the present study to ensure the quality of precipitation data. We found no significant difference in average monthly, seasonal (wet and dry seasons), and annual precipitation, as well as the temporal trends between the two sets of data.

2.3.3. Potential Evapotranspiration

[14] To account for effects of climatic variability on river discharge, we initially collected data on pan evaporation. However, due to the evaporation paradox in the study region as recently reported by *Cong et al.* [2009], pan evaporation is not a suitable indicator for climatic variability and thus was not used in this study. Instead, we used both potential evapotranspiration (PET) and precipitation to represent climatic variability. PET was estimated through the Penman-Monteith equation recommended by the Food and Agriculture Organization (FAO) [*Allen et al.*, 1998]:

$$\mathrm{PET} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}, \tag{2}$$

where PET is the potential evapotranspiration (mm/day), R_n is the net radiation on land surface (MJ m^{-2} d^{-1}), G is the soil heat flux (MJ m^{-2} d^{-1}), γ is the psychometric constant (kPa/°C), T is the mean daily air temperature (°C), U_2 is the mean daily wind speed at 2 m in height (m/s), e_s is the saturated vapor pressure (kPa), e_a is the actual vapor pressure (kPa), and Δ is the slope of the vapor pressure temperature curve (kPa/°C).

[15] Daily PET was calculated for the whole period of 1956 to 2006 across the province according to equation (2). The yearly PET of Guangdong Province was obtained through the averaged yearly values of different meteorological stations of GPHB.

2.3.4. River Discharge and Water Budget

[16] All river discharge and human water consumption data were obtained from the summary report by GPHB (unpublished data, 2004). Because river flows cross the borders between Guangdong Province and other neighboring provinces, the water budget method was used to calculate realized water yield (RWY) contributed solely from Guangdong Province as follows:

$$\mathrm{RWY} = \mathrm{ODS} + \mathrm{ODP} - \mathrm{ID}, \tag{3}$$

where ODS is the outflow discharge to sea, ODP is the outflow discharge to other provinces, and ID is the inflow discharge from other provinces.

[17] Data on ODS, ODP, and ID in the period between 1956 and 2002 were obtained from GPHB (unpublished data, 2004), while those for the period between 2003 and 2006 were compiled by this study using the same method used by GPHB (unpublished data, 2004). RWY is the balance between outflow and inflow discharge, reflecting the realized water resources produced solely from Guangdong Province. The intra-annual variation of RWY ($\mathrm{CV}_{\mathrm{RWY}}$) was also calculated using a method similar to equation (1).

2.3.5. Variables Affecting River Discharge Changes

[18] In this research, we assumed that river discharge changes or variations ($\Delta Q_{\mathrm{total}}$) are mainly influenced by climatic variability ($\Delta Q_{\mathrm{climate}}$) and human activities ($\Delta Q_{\mathrm{human}}$). As mentioned earlier, climatic variability is represented by changes in PET and precipitation, while human activities include forest changes, water consumption (e.g., water uses for industries, town living, rural living, arable land irrigation, garden irrigation, and fisheries), and construction of reservoir storage. To quantify the relative contribution of these variables to river discharge changes, we applied the following procedures.

[19] First, trend analysis was conducted on annual and seasonal river discharges. If there was a significant trend, further analyses were implemented using both double mass curve and the Cusum test [*Hinkley*, 1971] to determine breakpoint(s). A breakpoint is the division point after which a hydrological series is significantly altered. If there was a breakpoint, subsequent analysis was conducted only on hydrological series for the period after the breakpoint.

[20] Second, for the post-breakpoint period, the effects of total human activities on river discharge ($\Delta Q_{\mathrm{human}}$) can be quantified by removing the effects of climatic variability ($\Delta Q_{\mathrm{climate}}$) from total river discharge variation ($\Delta Q_{\mathrm{total}}$). A double mass curve of cumulative river discharge versus cumulative climate variable representing climatic variability can serve this purpose. Various researches have demonstrated that climatic variability can be effectively represented by precipitation variations when assessing its influence on hydrology. For example, *Milly and Dunne* [2002] found that precipitation variation plays a predominant role in forcing runoff variability. *Vogel et al.* [1999] investigated 1447 watersheds in the United States and found that streamflow is more sensitive to precipitation changes than to potential evapotranspiration. *Sankarasubramanian et al.* [2001] used precipitation variation as climatic variability to assess streamflow sensitivity. Thus, in this study, precipitation changes were used to represent climatic variability. Therefore, a double mass curve of cumulative river discharge against cumulative precipitation was constructed. The effects of total human activities on river discharge at any point of time t, $\Delta Q_{\mathrm{human}}(t)$, can be estimated by the following equation:

$$\Delta Q_{\mathrm{human}}(t) = Q_{\mathrm{cd}}(t) - Q_{\mathrm{cd}}(t-1), \tag{4}$$

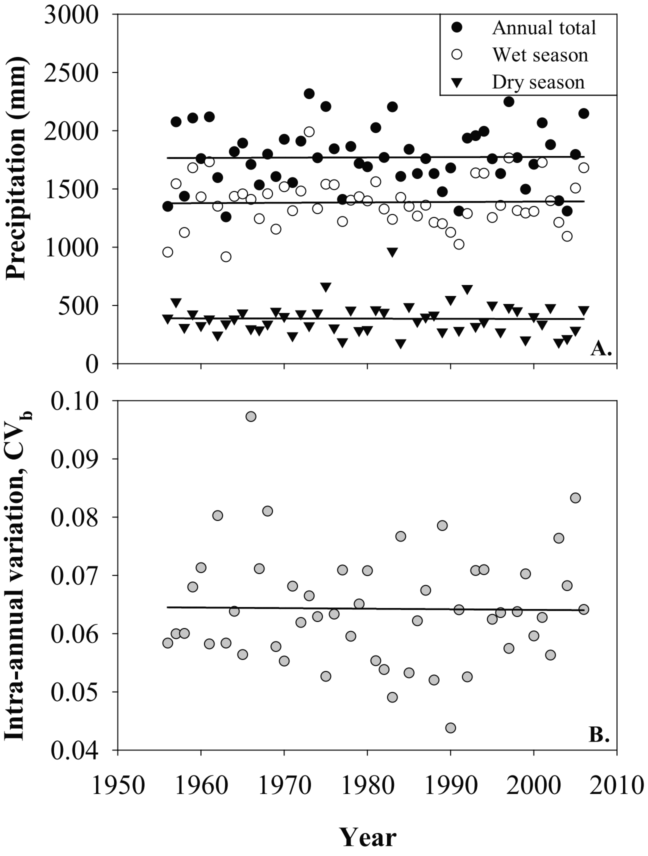

Figure 3. Long-term precipitation trends in Guangdong Province in 1956–2006 (a) over annual, wet, and dry season intervals and (b) for intra-annual variation CV_p.

where $Q_{cd}(t)$ and $Q_{cd}(t-1)$ are cumulative deviations between observed discharges and predicted values based on the linear relationship derived from the prebreakpoint period at times t and $t-1$, respectively.

[21] Finally, once the effect of total human activities (ΔQ_{human}) on river discharge is known, we can then estimate the effect of forest coverage change on river discharge by deducting the effects of other human activities (water consumption and construction of reservoirs).

[22] From a regional water cycling perspective, RWY is influenced by precipitation, evapotranspiration, human water consumption, forest changes, and reservoir systems. Human water consumption is the total net water consumption used for industries, town living, rural living, arable land irrigation, garden irrigation, and fisheries. It is a direct measure for water loss from the whole province. Forest changes (harvesting or reforestation) can affect the amount of river discharge through influence on evapotranspiration, infiltration, and flow timing, while the construction of reservoirs can directly change the flow magnitude and timing downstream. Historic data on reservoir capacity and human water consumption in Guangdong Province during the study period (1956 to 2006) are from GPHB. The reservoir capacity is the maximum design capacity.

2.4. Statistical Analysis

[23] Time series analysis was used to test for a significant relationship between forest recovery and river discharge in Guangdong Province based on long-term data on forest cover and hydrological variables (RWY over annual and seasonal intervals). Time series analysis (e.g., cross correlation) is a powerful and robust statistical technique in which long-term data requirements (e.g., longer than 50 years of records for annual variables) are met. To conduct time series analysis, the two tested series must be filtered or prewhitened to remove autocorrelation within each individual series [*Chatfield*, 1989; *Jassby and Powell*, 1990]. Following the recommendations of *Box and Jenkins* [1976] and *Chatfield*, [1989], we prewhitened each series with autoregressive integrated moving average (ARIMA) models before cross-correlation analysis was conducted. For each hydrological series, numerous ARIMA models were tested and the best one in terms of achievement of stationarity of the residual series was chosen for cross-correlation analysis. The same was done with forest cover time series. All time series analyses were conducted using the software STATISTICA developed by StaSoft, Inc. [*StaSoft Inc.*, 1995].

3. Results

3.1. Long-Term Precipitation and PET Trends

[24] No significant trends in precipitation over annual, wet and dry season intervals (Figure 3a), or intra-annual variation of precipitation (CV_p) (Figure 3b) were detected for the study period 1956–2006. There was no a significant trend on long-term annual PET in Guangdong Province for more than 50 years (Figure 4).

3.2. Long-Term River Discharge

[25] The long-term annual averages of ID, ODS, and ODP in 1956–2006 were 1313, 2235, and 13 mm, respectively. The outflow discharge to other provinces was minor compared to the other two flow discharges (ID and ODS). Because of this, ODS represents a dominant water flux through the whole province. The inflow discharge from the neighboring provinces accounts for about 60% of the total discharge flowing out to the sea, while the rest (40%) is produced within Guangdong Province.

[26] As shown in Figure 5a, there are no significant trends in RWY in either the wet season or annual intervals, even though a slight upward trend existed in the RWY over the

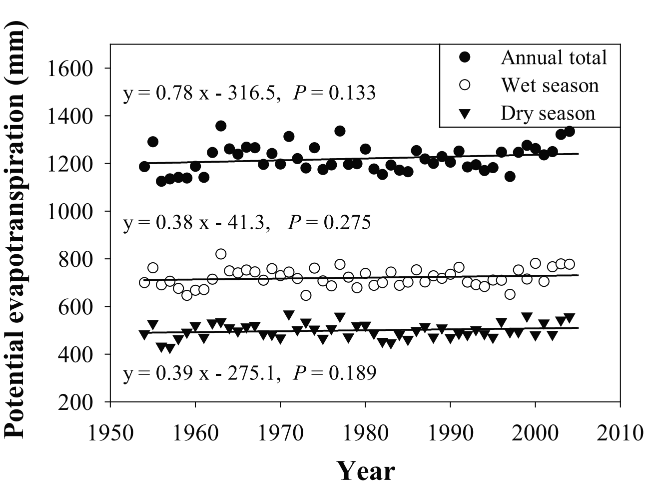

Figure 4. Potential evapotranspiration in Guangdong Province from 1956 to 2006.

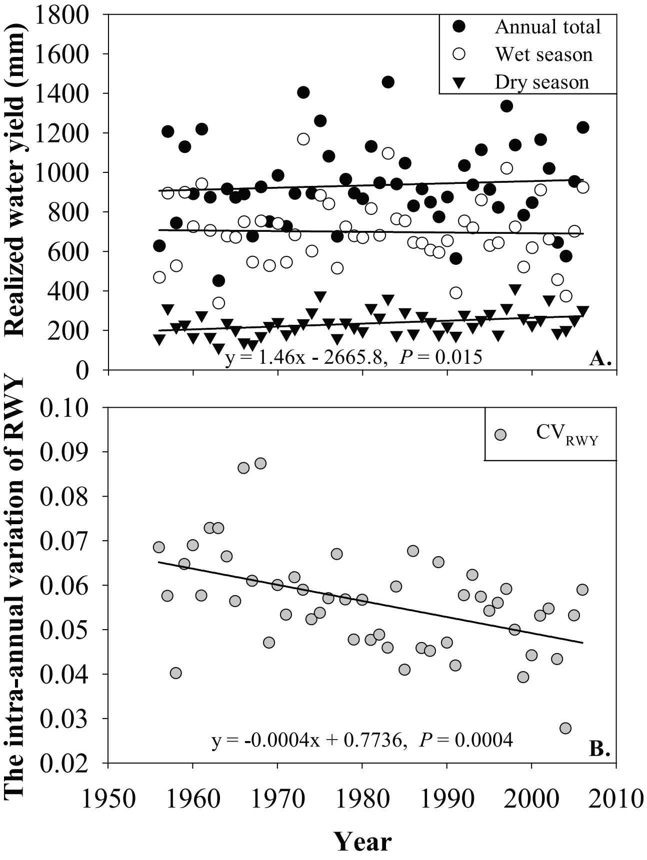

Figure 5. Realized water yield (RWY) in Guangdong Province from 1956 to 2006: (a) the average amount over annual, wet season, and dry season intervals and (b) the intra-annual variation of RWY (CV_{RWY}).

annual interval. However, the RWY in the dry season significantly increased over the past 50 years ($y = 1.4647x - 2665.8$, $R^2 = 0.12$, $p = 0.015$). Because there was no statistical trend in precipitation in the dry season (Figure 3a), the increasing trend in RWY in the dry season may be caused by factors other than precipitation. The average increment rate was 1.46 ± 0.18 mm/yr, significantly different from 0 at $\alpha = 0.05$. The intra-annual variation of RWY significantly decreased ($p = 0.0004$) mainly due to increased RWY in the dry season (Figure 5b).

[27] To further analyze RWY in the dry season, we compared the ratios of monthly RWY to monthly precipitation between the four periods. No statistical difference was found in the ratios of the dry and wet seasons among the first three periods (1956–1961, 1962–1986, and 1987–1994; Figure 6 and Table 1). However, a significant difference in the ratios of the dry season between the first three periods and the period 1995–2006 was detected ($p < 0.05$; Figure 6 and Table 1), suggesting that the increasing trend of the RWY in the dry season in the whole study period (Figure 5) was mainly due to the increased RWY in the period 1995–2006. This result is further supported by the double mass curve (a plot of cumulative precipitation against cumulative discharge, RWY) shown in Figure 7. From this curve, a reflection point (year 1992) was apparent, indicating that RWY in the dry season increased in 1992. In addition, the Cusum test also detected the year 1992 as the breakpoint in the RWY of the dry season. Clearly, the significant increasing trend of RWY in the dry season mainly resulted from its change since the early or mid-1990s. Our analysis showed that the change in the ratios of monthly RWY to monthly precipitation in the wet season were not statistically significant among all four study periods.

3.3. Forest Change and River Discharge: Water Budget Analysis

[28] Using the year 1992 as a breakpoint and based on the calculation procedure described in section 2, we estimated that the effect of total human activities on river discharge is 42 mm annually for the period 1993–2006 (Table 2). During this period, urbanization contributed to 1.1 ± 0.3 mm annually, while water consumptions accounted for 0.8 ± 0.7 mm. Thus, the combined effect of forest coverage and reservoir system increases caused a total of 41.7 mm river discharge increase in the dry season from 1993 to 2006. In addition, such a flow increase is judged to be mainly associated with forest coverage change.

3.4. Forest Cover and River Discharge: Statistical Analysis

[29] There were no significant relations between forest cover and the RWYs over annual, dry season, and wet season intervals (Table 3). Lack of statistical significance between forest cover and river discharge suggests that forest recovery has not caused significant reduction in river discharge at the regional scale of Guangdong Province in the past 50 years.

4. Discussion

4.1. Variables Contributing to River Discharge Changes: Water Budget Analysis

[30] Since only RWY of the dry season had a significant increasing trend and the breakpoint is the year of 1992, we analyzed and discussed variables contributing to river discharge changes for the period 1993–2006 with a focus on RWY of the dry season. Hydrological variables including annual and seasonal RWYs in the period 1956–1991 were not significantly altered and thus are not further discussed.

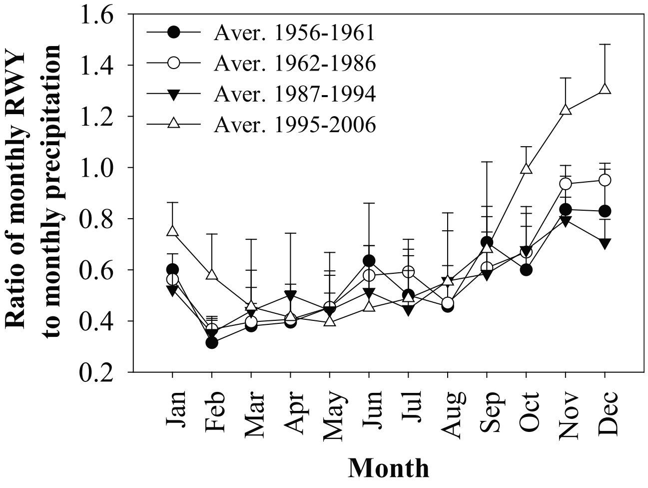

Figure 6. Ratios of monthly RWY to monthly precipitation in the four periods.

Table 1. Ratios of Mean RWY to Precipitation in Both the Wet and Dry Seasons During the Four Periods in Guangdong Province

Period	Precipitation, Wet Season (mm)	Precipitation, Dry Season (mm)	RWY, Wet Season (mm)	RWY, Dry Season (mm)	RWY/Precipitation, Wet Season (mm)	RWY/Precipitation, Dry Season (mm)	Total RWY/Total Precipitation (mm)
1956–1961	1412	396	742	227	0.53	0.57	0.54
1962–1986	1390	390	711	223	0.51	0.57	0.53
1987–1994	1310	407	652	230	0.50	0.57	0.51
1995–2006	1409	359	682	270	0.48	0.75	0.54

4.1.1. Increase of Impervious Surface due to Urbanization

[31] Percentages of impervious surface area due to urbanization (e.g., road construction, building and house construction, and parking lot expansion) increased continuously and significantly from 4.1% to 8.5% ($y = 0.096x - 184.47$, where x represents years 1956–2006 and y is the impervious surface area percentage; $R^2 = 0.9534$, $p < 0.0001$) in Guangdong Province from 1956 to 2006 according to the recorded data of the Guangdong Provincial Bureau of Land Resources. The average increase rate was 0.096% each year, which was significantly different from 0 at $\alpha = 0.01$. Increasing impervious surface areas can increase water yield due to their waterproofing nature. Using the empirical coefficients of runoff to rainfall (0.75 ± 0.15 in the wet season and 0.5 ± 0.10 in the dry season) developed by GPHB (unpublished data, 2004) based on long-term measurements in urban areas, we estimated that the contributions of urbanization to river discharge in the dry season would be 1.1 ± 0.3 mm/yr for the period 1993–2006 (also see Table 2).

4.1.2. Change in Human Water Resources Consumption

[32] The total net water consumption includes the consumed water for industry, town living, rural living, arable land irrigation, garden irrigation, and fisheries. Although water consumption rates (percentage of total net water consumption to total water withdrawal) were significantly decreased ($p < 0.0001$), mainly due to improvement of water resource utilization technology, the total net water consumption amounts in Guangdong Province were significantly increased ($y = 0.81x - 1523.2$, where x represents years 1956–2006 and y represents human net water consumption in millimeters; $R^2 = 0.96$, $p < 0.0001$). The average increase rate was 0.81 mm each year, which was significantly different from 0 at $\alpha = 0.01$. On the basis of long-term water consumption data, we estimated that the contribution of the total water consumption category to river discharge in 1993–2006 would be 0.8 ± 0.7 mm/yr in the dry season that would otherwise be delivered to rivers (Table 2).

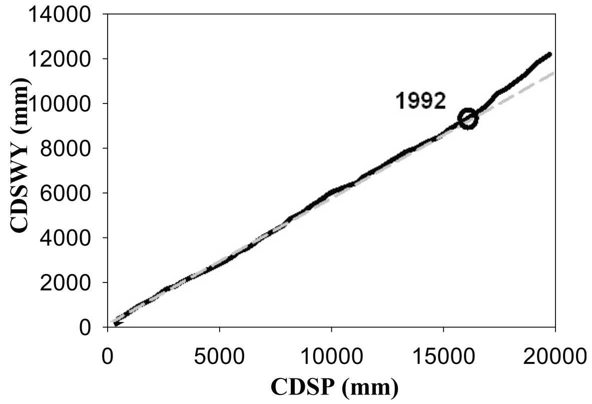

Figure 7. Double mass curve between cumulative annual precipitation in Guangdong Province in the dry season (CDSP) and cumulative annual realized water yield in the dry season (CDSWY) from 1956 to 2006.

4.1.3. Effects of Climatic Variability

[33] The estimated effects of climatic variability on the RWY of the dry season in 1993–2006 was −35.4 mm annually (Table 2). The negative value suggests that river discharge in the dry season would have been reduced as a result of climatic variability over the period 1993–2006. This negative effect of climatic variability on the RWY of the dry season was judged to be caused by increased PET ($p < 0.05$) in the period 1993–2006.

4.1.4. Influence of Forest Recovery and Reservoir Systems

[34] The combined effect of forest recovery and construction of reservoir systems on the RWY of the dry season in 1993–2006 was estimated to be 41.7 mm annually (Table 2). This accounts for about 99% of the discharge increase caused by total human activities, suggesting that forest recovery and construction of reservoir systems play a major positive role in the dry season flow augment in Guangdong Province. This augment was mainly used to offset flow reduction (−35.4 mm/yr) due to increased PET with a net increase of 6.6 mm/yr.

[35] Where did this flow increase in the dry season of 1993–2006 come from when there was no significant change or even slightly decreasing in precipitation? Clearly, water yields must have been shifted from the wet season to the dry season over the past 50 years (particularly in the period 1993–2006), which caused significant increases in the RWY in the dry season. We believe that forest recovery and reservoir systems are the possible factors responsible for the shift because both factors play a similar role in extending water residence time in the watersheds and consequently enhancing river discharge in the dry season. During the wet seasons, a more forested watershed allows more soil water

Table 2. Average Respective Contributions of Human Activities and Climate Variability on Dry Season Streamflow Deviation (1993–2006)

Components	Contribution (mm/yr)
ΔQ_{total}	6.6
$\Delta Q_{\text{climate}}$	−35.4
ΔQ_{human}	42.0 ± 1.4
$\Delta Q_{\text{forest change/reservior}}$	41.7
$\Delta Q_{\text{urbanization}}$	1.1 ± 0.3
$\Delta Q_{\text{water consumption}}$	−0.8 ± 0.7

Table 3. Time Series Analysis (Cross Correlation) Between Forest Cover (%) and Realized Water Yield Variables[a]

ARIMA		Cross-Correlation Coefficients						
Variable	Model	lag = 0	lag = 1	lag = 2	lag = 3	lag = 4	lag = 5	lag = 6
RWY (annual)	ln(1,4,1)	0.005	0.085	0.003	−0.003	0.037	−0.09	0.005
RWY (dry season)	ln(2,2,0)	0.029	0.036	−0.021	−0.084	−0.158	0.177	0.067
RWY (wet season)	ln(1,2,1)	−0.159	0.018	−0.007	−0.079	0.057	0.088	−0.159

[a] Autoregressive integrated moving average (ARIMA) model for the forest cover is ln(2,2,0). RWY, realized water yield; *, significance with 95% confidence level.

infiltration and groundwater recharging, which can increase flows in the dry seasons.

[36] Changes in the total reservoir capacity of Guangdong Province are shown in Figure 8. The greatest change occurred between 1961 and 1962. Since then, the reservoir capacity has been increasing steadily. After 1999, the total reservoir capacity remains unchanged. Table 4 shows the changing patterns of reservoir capacity, forest cover, and RWY in the four periods. The reservoirs in Guangdong Province were mainly built for the purposes of flood protection because storms in the wet season usually cause flooding in downstream areas (GPHB, unpublished data, 2004). Existence of the reservoirs can help control flooding for several days, but it is unlikely that they redistribute the river discharge from wet season to dry season.

[37] From period 1 to period 2, the reservoir capacity dramatically increased. The reservoir capacity in period 2 was 10 times as large as that in period 1. Despite dramatic increases in reservoir capacity from period 1 to period 2 (or period 3), the ratios of RWY to precipitation in the dry season showed no significant difference between two periods (or between periods 1 and 3) as shown in Table 1. This, together with the purposes of reservoir construction, clearly suggests that the dramatic increases of reservoir capacity did not cause significant changes in river discharge (RWY) in the dry season. The largest changes in RWY and the ratios of RWY to precipitation in the dry season occurred from period 3 to period 4 (Table 1) and corresponded to the dramatic change in forest cover (Table 4). Combined with the double mass curve and water budget analysis, we believe that forest cover change likely plays a role in increasing river discharge in the dry season.

[38] It is commonly understood that fully established forests can greatly increase soil infiltration and thus groundwater recharg [*Albert and Keenan*, 2007]. The increased groundwater can discharge into river systems, particularly in low flow seasons. In Guangdong Province, large-scale forest recovery over the past 50 years (particularly in the period 1993–2006) would likely convert water in the wet season to the dry season through enhanced infiltration-recharging-discharging processes. However, the exact contribution of forest recovery to river discharge at this regional scale is difficult to quantify by using the water budget method because many variables likely affect river discharge in a cumulative way; it is challenging to quantitatively separate their relative contributions. However, the water budget method does provide a useful tool to examine the role of forest recovery in hydrology, among many other variables.

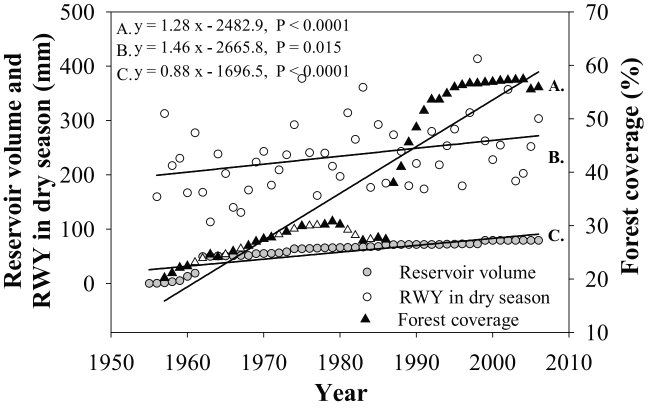

Figure 8. Forest coverage, reservoir capacity, and realized water yield of the dry season from 1956 to 2006.

4.2. Impacts of Forest Recovery on River Discharge: Statistical Approach

[39] Our time series analyses did not detect significant changes of river discharge (RWY in annual, wet season, and dry season intervals) as a result of forest recovery. In other words, large-scale forest restoration from about 20% in 1956 to 57% in 2006 did not cause significant water reduction over the past 50 years in Guangdong Province. This finding is consistent with some large-scale watershed studies [e.g., *Antonio et al.*, 2008; *Guo et al.*, 2008]. The common explanation for water reduction due to reforestation is that actual evapotranspiration is increased after forests are re-established because tree roots can absorb the water in deep soil and forest canopy can intercept some rainfall, so less water becomes river discharge [*Zhang et al.*, 2001; *Brown et al.*, 2005; *McVicar et al.*, 2007b]. However, the rationality of the explanation is based on the assumption that there is enough surplus potential evapotranspiration after all available soil water is evaporated. However, as shown in Figure 2, the annual PET is approximately 69% of the annual precipitation and about 52% in the wet season, which shows that it is the PET, not the available liquid water, that controls the actual evapotranspiration in this region, particularly in the wet season. Although the increase in forest cover can increase evapotranspiration due to increases in root systems and leaf areas, the actual evapotranspiration is constained due to limited PET. Since the forest cover is unlikely to cause changes in energy availability (PET) and our data also show

Table 4. Change Patterns of Reservoir Capacity, Forest Cover, and RWY in Dry Season in the Four Periods in Guangdong Province

Period	Average Reservoir Capacity (mm)	Forest Cover (%)	RWY in Dry Season (mm)
1: 1955–1961	5.95 (0.077–18.96)	21.7 (20.2–23.1)	227
2: 1962–1986	59.85 (49.44–71.46)	28.0 (24.1–30.8)	223
3: 1987–1994	71.63 (71.46–72.17)	48.3 (38.0–54.7)	230
4: 1995–2006	77.15 (72.17–79.40)	56.6 (55.5–57.4)	270

that there is no significant change in PET, we expect that any change in forest cover would not cause a significant change in actual evapotranspiration in Guangdong Province due to limited energy for evapotranspiration. In other words, actual evapotranspiration is much less sensitive to vegetation change in this humid region compared with those in any relatively dry regions. In addition, increased forest coverage can lengthen the flow paths to rivers, enhance soil infiltration, and, consequently, promote more groundwater recharges. Thus, we believe that forest recovery can store more water in the aquifers, which then slowly discharges into the river systems in the dry season.

[40] In this study, both water budget and statistical methods showed no negative effect of large-scale forest recovery on river discharge in Guangdong Province over the past 50 years. This conclusion is important because Guangdong Province is continuously implementing reforestation programs and there are serious concerns over water reduction due to reforestation. The conclusion is different from the general perception that carbon and water are trade-offs [*Jackson et al.*, 2005; *Sun et al.*, 2006] and that more trees will lead to less water. However, the trade-off relationship between forests and water is largely based on small-scale watershed studies. These conflicting results clearly demonstrate the importance of spatial scales. They also highlight that we must be cautious when extrapolating our results at the regional scale to other smaller scales. In addition, our research also suggests that forest recovery might play a positive role in redistributing water from the wet season to the dry season by promoting infiltration-recharging-discharging processes in Guangdong Province over the past 50 years. This result is beneficial because Guangdong Province will need more water in the dry seasons with more economic development and urbanization in the future.

[41] Our results have important strategic implications as Guangdong Province continues its reforestation programs. The growing need to store more carbon in the forests and rehabilitate environmental problems will continue to provide incentives for Guangdong Province to extend its reforestation programs. *Zhou et al.* [2008] reported that over the 10-year period (1980s to 1990s) the reforestation program in Guangdong Province has increased total carbon storage by 41.67 Tg and forest carbon density by 1.58 Mg cha^{-1}. Our results will further support future reforestation programs as they will not cause significant water reduction at the regional scale in the province. However, more studies are needed to examine the forest-water relationship at smaller spatial scales and between different forest types so that more detailed reforestation programs can be designed and implemented.

5. Conclusions

[42] In this paper, we applied the combination of water budget with statistical approaches to examine the possible effects of large-scale forest recovery on river discharge at the regional scale of Guangdong Province based on 50 years of long-term data. On the basis of consistent results from both approaches, we concluded that forest recovery from 20% to 57% did not cause a significant negative effect on river discharge. Instead, forest recovery is estimated to play a positive role in redistributing water from the wet season to the dry season by promoting infiltration-recharging-discharging processes. Despite the common belief of the trade-off relationship between carbon (forests) and water, our results demonstrate that carbon and water may not necessarily conflict in large-scale humid regions. Our study also demonstrates that a combined research strategy is useful in addressing the forest-water relationship at a regional spatial scale.

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