Effects of reservoir storage on streamflow in Western Cape, South Africa

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Abstract

The construction of dams can significantly alter river flow, thus affecting downstream aquatic and riparian environments. As human populations continue to grow, the demand for water, which is imperative for survival, will also grow. The Western Cape Province, South Africa is home to a major metropolis, Cape Town, which relies heavily on reservoirs for their water supply. Therefore, reservoirs are essential to store water from major storms and rainy seasons to use during dry months. The objective of this study is to determine how regulation and water use impacts streamflow downstream of reservoirs. A paired watershed approach was used to examine discharge (Q) in gauged dammed and undammed rivers selected based on similar sized gauged catchment areas for the period of available records. Q data from streamflow gauges and precipitation (P) data were acquired from the Hydrologic Information System (HIS) and Climate Systems Analysis Group (CSAG). Mean Annual Runoff (MAR) comparisons, flow duration analysis (probability of daily Q), and annual water balance calculations were conducted to characterize varying behaviors in flow along with a stationarity test for annual-P (Sun et al., 2019). Sequential air photos of selected dammed river reaches were used along with Q data to develop hydraulic geometry relationships (Width = aQ_b) that could be used to predict wetted width distributions. Precipitation time series data were analyzed for stationarity using trend and autocorrelation analyses. These tests indicated that lag 1 autocorrelation coefficients are statistically significant (95% confidence) for annual data but generally insignificant on decadal timescales, suggesting overall stationary behavior with no significant long-term trends. MAR for dammed and undammed rivers of varying size was compared for the interval 2010-2018. Data indicates that the undammed site of smaller size to have greater values and the moderate size to have lesser values than their paired dammed rivers. Comparison of flow duration analysis for paired streams indicates that the undammed river of smaller size sustained higher flows during its entire recorded period on flow levels (high, moderate, and low flows) and showed less inter-annual variability while the moderate size river sustained higher flows during only a portion of its recorded period (moderate flows) and showed similar inter-annual variability. Wetted width analysis of the smallest dammed river shows a direct linear relationship to Q and large inter-annual variability in width, like Q. Flow duration analysis for the largest dammed site indicates the largest inter-annual variability in any of the sites and runoff shows a declining trend since its construction period. Annual water balance calculations indicate that Evapotranspiration (ET) is increasing at 2 dammed sites, with a dammed site having greater mean ET than its paired undammed site. These results suggest that the damming of rivers in Western Cape is significantly impacting the downstream water availability and alternative sources of water needed to be considered or significant measures to reduce ET levels must be addressed should reservoir storage continue. The availability of water is becoming increasingly unpredictable with climate change and population growth, thus it is essential South Africa understands how their human infrastructure and consequences of water retention and use affect their downstream water availability and river habitats.

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Introduction

An easily accessible reservoir can be used for municipal water supplies, irrigation, hydroelectric power or flood control. Some reservoirs are used for multiple purposes, but the construction of dams can come with many environmental consequences such as altering a river's flow regime, affecting water temperature and quality, disrupting sediment movement, and affecting riparian habitat (WCD, 2000; Magilligan et al., 2003; Tealdi et al., 2011). Only approximately one third of the world's longest rivers remain free flowing (Grill et al., 2019) and many smaller rivers are also disrupted. Despite concerns about their consequences, dam-reservoir systems appear to be a necessity in order to provide water for rapidly growing human population centers. Climate change affects precipitation and streamflow predictability, generating challenges in reservoir operation in regions where communities rely heavily on reservoir storage. It also places these communities at risk in times of drought. A prime example of this is in the Western Cape, South Africa, which faced a water crisis in 2018.

Background

The Western Cape, South Africa is a province home to a major metropolis, Cape Town, that relies heavily on the use of reservoirs for water supply. Western Cape's temperate climate has seasonal precipitation with pronounced wet and dry seasons (Figure 1). Precipitation mainly occurs in the winter months (May-August). Topography is complex with mountainous regions close to the ocean (Figure 2). This topographic control limits the size of watersheds in the Western Cape. The combination of small watersheds and seasonal precipitation results in relatively small and seasonal stream discharges. This creates the need for multiple reservoirs to provide water to the region for industrial, municipal, and cultivation purposes. These reservoirs are used primarily to store water for municipal and irrigation water use.

Figure 1 *Average monthly rainfall in Cape Town, South Africa (South African Weather Service, 2018).*

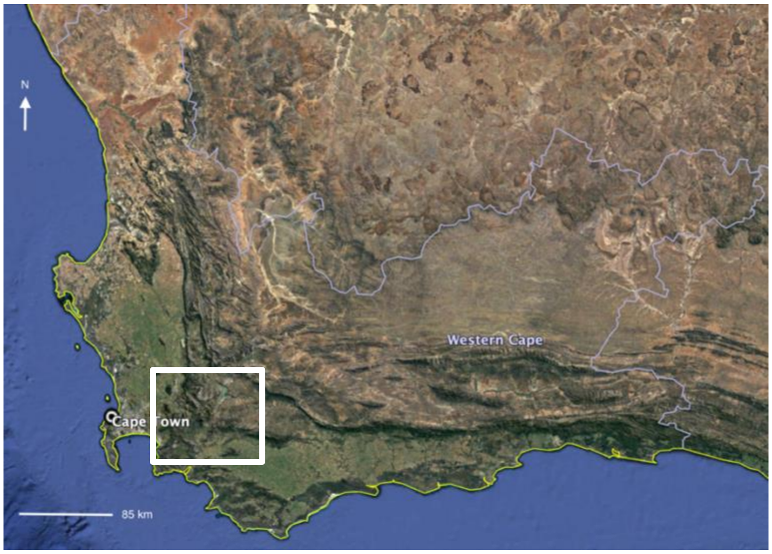


Figure 2 *Topography of Western Cape, South Africa. White box shows location of study region (Figure 3).*

Cape Town is part of the Western Cape Water Supply System (WCWSS), a water network that consists of six major dams ('Big Six') and many minor dams (CCT, 2019). These primary dams can store 898,221 million liters (ML) of water, which constitute 99.6% of the city's water storage capacity (CCT, 2019). In early 2018, the City of Cape Town was on the verge of a water crisis having almost entirely run out of their water supply. Due to a severe drought beginning in 2015, reservoir levels had already been declining. The crisis was heightened in 2017 to early 2018 when water levels fluctuated between 15-30% of their storage capacity and the largest reservoir (The Waterskloof) dropped to 17.5% of its storage capacity (Muller, 2017). The city was preparing for the anticipated 'Day Zero,' a day in which the government would shut the city's taps off had dam levels fell to 13.5% (Arcanjo, 2018). Tight water restrictions, along with an increase in rainfall in winter of 2018, led to rising water levels and the city's water crisis had temporarily halted as reservoir levels rose nearly 70% of their storage capacity by the end of the rainy season (Pitt, 2018).

Previous Work

While many studies have been conducted globally on the effects of dams on streamflow, very few have been conducted in Western Cape. Pre-post dam construction studies in other regions have determined a significant reduction in days flooded (Maingi and Marsh, 2002; Choi et al., 2005; Magilligan et al., 2013), documented changes in sedimentation rates (Ronco et al., 2010), and evaluated the effects of dams on prolonging periods of reduced flows (Nataša and Matjaž, 2013). Reservoir regulation has also shown to alter the timing of discharge regimes (Yang et al., 2004). Another study found that the high densities of small dams in Western Cape significantly reduced low flow discharge (Mantel et al., 2010). This impact on downstream low flows has also been observed in other regions of the world (Poff and Hart, 2002; Yang et al., 2017; Lee et al., 2018), but more research is needed on Western Cape regulated rivers. It is essential for more research on the hydrological impacts of reservoir storage in water stressed regions such as Western Cape to be conducted, considering the numerous rivers that are dammed in the region.

Methods

Approach: The objective of this study is to understand the differences in streamflow downstream of undammed and dammed rivers in the Western Cape. This research will provide more insight into how reservoir storage impacts watersheds of various sizes, by examining: annual precipitation, annual runoff, peak discharge, and the probability distribution of daily discharge in regulated and non-regulated Western Cape watersheds. A paired watershed approach is used, a basic method that is used around the world and has become a predominant method to quantify the impacts of water management on catchment-scale hydrology requiring a minimum of two watersheds (Clausen and Spooner, 1993; Zégre et al., 2010; Ssegal et al., 2019). In this study, the approach is designed to specifically compare dammed and undammed rivers with similar catchment areas, by comparing unit runoff. In addition, inter-annual variations in stream discharge distributions using flow duration analysis on both dammed and undammed rivers are evaluated as well as width of one of the selected dammed rivers.

Hypothesis

The effects of reservoir storage on river flow and habitat by comparing dammed and undammed rivers are examined through the following hypothesis:

i. H_1: Reservoir storage causes significantly reduced river discharge (*Q*) and annual runoff compared to similar undammed rivers
Null: Reservoir storage does not significantly affect streamflow (implies that reservoir size and withdrawals are insignificant relative to river size).
ii. H_2: Reservoir storage shifts the probability distribution of wetted widths towards smaller widths and causes greater inter-annual variability in riparian water supply
Null: Reservoir storage has no impact on wetted width distributions
iii. H_3: Annual precipitation has significantly changed in the past 40 years, reflecting climate change
Null: Annual precipitation has not significantly changed in the past 40 years

Table 1: Hypothesis and methods to test hypothesis

Hypothesis	***Methods to Test H***
H_1	*Runoff comparison among rivers; Q-Basin area analysis, flow duration analysis, streamflow trend analysis*
H_2	*Q vs Wetted Width analysis, use of flow duration analysis to evaluate wetted with probability*
H_3	*Test for stationarity of annual precipitation*

Selection Criteria and Discharge (Q) Data

Figure 3 *Study site locations. Red markers represent sites of dammed rivers: (A) The Waterskloof Dam, (B) Berg River Dam, (C) Wemmershoek Dam. The markers are placed at the site of gauges, located at dam outlets. Orange markers represent sites of dammed rivers directly downstream of a dam where gauged data was obtained: (1) Berg River, (2) Wemmershoek River, (3) Sonderend River. Pink markers represent sites of undammed rivers where gauged data was obtained: (1) Onrus River, (2) Eerst River.*

Daily average discharge data at streamflow gauges were acquired from the South Africa Department of Water and Sanitation Hydrological Information System (HIS, 2019). Three gauges on dammed rivers and two gauges on undammed rivers were selected for analysis (Figure 3). Stream gauges having available flow data recorded with overlapping time periods were used in the analysis. Of all five chosen sites in Western Cape, this ranges from 8-45 years of recorded flow data. Sites were selected based on longest recorded periods of data and similar gauged catchment areas, a paired watershed approach (Table 2). This is done to make appropriate comparisons between dammed and undammed rivers. However, the largest dammed site is compared to itself, due to lack of data for a similar sized river.

The selected dammed river sites are impounded by 3 of the 6 major dams that are part of the WCWSS. Data that are available for these gauging stations includes annual volume of water, daily average discharge, and annual peak discharge. All data were recorded in water years (WY), Oct 1-Sep 30, a method commonly used in hydrologic modeling to categorize precipitation totals in a 12-month period without dividing hydrological seasons (Suhula et al., 2017).

Table 2: Summary of selected sites

River name	Onrus	Berg	Wemmershoek	Eerst	*Sonderend
Dam name		Berg	Wemmershoek		Waterskloof
Catchment Area (km$_2$)	23	83	118	183	516
Period of available recorded data	1996-2018	2008-2018	2009-2018; 2014 absent	1980-2018	1974-2018
Coordinates of gauges	34°21’32”S 19°15’14”E	33°54’16”S 19°03’17”E	33°51’08”S 19°02’33”E	33°56’59”S 18°50’18”E	34°05’31”S 19°17’39”E

***Compared to itself**

Annual Precipitation (P) data

South Africa’s range of biomes comes with varying amounts of rainfall that is spatially heterogeneous (Figure 4) from ENSO events (Lakhraj-Govender and Grab, 2019). Annual-*P* data was obtained from areas that were closest to the selected gauges. Data were obtained from the Climate System Analysis Group (CSAG, 2019a) where rainfall data were available for two of the three dam sites: the Wemmershoek Dam and Waterskloof Dam. Data were recorded beginning in 1981 and 1982, respectively. HIS data were also utilized to obtain rainfall data at the Berg River Dam (recorded since 1980) and 5 km from the Eerst River gauged site (recorded since 1999). Precipitation data were absent for the smallest site, the Onrus River. For each site where precipitation data were available, mean and standard deviation of the annual precipitation was determined. These statistics were used to determine the coefficient of variation of precipitation (CV = std./mean), which were compared among the stations and used to evaluate rainfall-runoff relationships for each station.

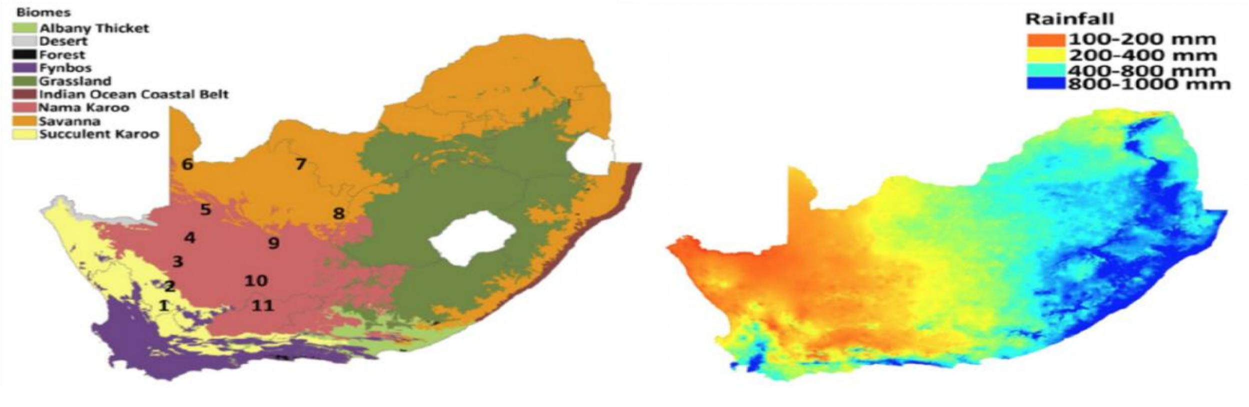


***Figure 4** Biomes and total rainfall amounts in South Africa (Shackleton et al., 2015).*

To test for the stationarity of precipitation, a stationarity test is used (Sun et al., 2018), which not only tests how stationary climatic variability is by observing if the mean remains constant over climatic timescales (10-years in this study), but in addition uses autocorrelation. Autocorrelation moves the data in time and computes how correlated it is with the unchanged/original time series while measuring the lag as time proceeds. In this case, the time series is deemed stationary if the mean stays relatively constant and the autocorrelation solely depends on where the relative position is in the time series. In this study, the most optimal case is by estimating the mean from the longest available records, in which 95% confidence intervals (CI) are used. Autocorrelation estimates of the time series for lags were computed manually in Excel.

Mean Annual Runoff (MAR) and Water Use Calculations: Average annual *Q* data was used to calculate runoff (m). Runoff = Average *Q* (m^3 s^{-1}) x seconds in a year (s yr^{-1}) x 1/catchment area (m^2). These MAR data were compared with precipitation data for each watershed to obtain MAR as a percentage of precipitation. MAR was subtracted from MAP for each basin to calculate watershed water use. In river basins without reservoirs, water use is primarily natural evapotranspiration (ET) (Water Use=ET ± change in storage). In river basins with reservoirs, water use includes natural ET + evaporation from the reservoir + export of water for human water use. Water Use can also be expressed as a percentage of precipitation for each site. However, due to the absence of change in storage data (human consumption) for each specific dam, ET values include the change in storage values that is unknown (ET=ET± change in storage).

Runoff-Basin Area Relationships: Calculation of annual runoff data accounts for the varying size of each watershed. Discharge, however, often varies significantly with basin area. In dry regions, the depth to the water table can be significant and discharge can decrease downstream due to riparian water uses. In wet regions, discharge can increase downstream due to groundwater discharge into the river channel. Therefore, runoff can vary systematically among basins due to watershed size, topography, and climate. This can be examined by evaluating discharge-basin area relationships for the data.

Daily Q probability calculations: Average daily discharges for recorded periods are ranked from largest to smallest values. Each site has varying number of values for the recorded period (n), and the individual values are then assigned a rank (R), beginning with 1 for the largest daily discharge value. The exceedance probability is then calculated as followed: P=[R/(n+1)]. These were then put into flow duration curves to observe long term characteristics of rivers over certain time periods.

Wetted River Width data: Air photos were obtained on Google Earth, to acquire wetted river width for a hydraulic geometric analysis. Due to rivers in Western Cape rivers having relatively smaller size and the resolution of images, air photos were only available along the Berg River site where an accurate width could be measured. Therefore, wetted width for the Berg River is compared to itself. Width was taken using Google Earth's ruler tool on a specific day where air photos had the best quality and resolution to most accurately measure the width. Location along the river was selected where the river bank is most distinguishable and closest to the gauged discharge site. Width of the river was then compared to recorded discharge on the day the air photo was taken. Many trials were performed to obtain standard deviations. This same process was repeated on several different days where daily discharge values were also available.

Uncertainties: Discharge and precipitation data were obtained from governmental agencies. Procedures for measurement of precipitation and streamflow are shared among nations (WMO). Discharge measurements indicate the amount of water passing a point on a stream. The drainage basin area that contributes to that point can be evaluated from topography. Assuming ideal conditions were made when taking measurements, errors for individual discharge measurements are usually in the range of 2-6% (Sauer and Mayer, 1992; Huhta and Sloat, 2005). Discharge measurements are correlated with water level measurements (gauge height), and these data are measured with field equipment.

Precipitation data are point measurements. Average precipitation within a drainage basin is usually estimated from multiple gauges. This is particularly important when precipitation is spatially heterogeneous due to topography, prevailing winds, and distance from the coast as in the Western Cape. Therefore, the estimate of annual precipitation from 1 rain gauge may not be sufficient for the large watersheds.

Missing Data: It would be ideal to have data every day, but at some locations, average flow data is not recorded on specific days. For free-flowing rivers, discharge can be estimated by developing comparisons (double mass curves) with similar rivers. This is more difficult to perform on streams with reservoirs. Therefore, years were rejected for which there were fewer than 250 data days from Oct 1 to Sep 30. This was a problem for a few years of missing precipitation data for 2/4 precipitation sites and flow data gauged downstream the Wemmershoek Dam, in which WY 2014 had 180 days of missing data. The entire hydrologic year was not accounted for, as this was assumed to be misrepresented.

Results

Annual Precipitation

The longest recorded annual-*P* time series goes back approximately 40 years. Time series of annual-*P* at all sites are shown in Figure 5, along with their relative trends. Each site receives different amounts of annual rainfall due to varying elevation and topography and shows large year-to-year variations, but they show similar patterns. Over these nearly four decades,

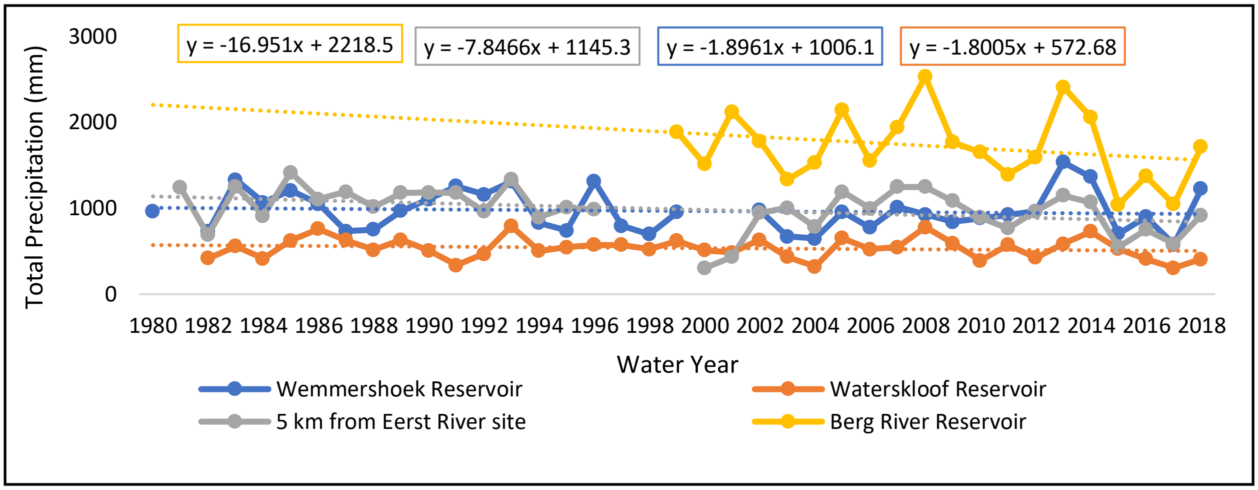


Figure 5 *Precipitation data at each gauged site given recorded period.*

precipitation remained relatively constant as the greatest change in trend is only 17 mm yr^{-1} at the Berg Reservoir site. The greatest deviation in mean for each site is during the recent drought years, where the water crisis occurred (WYs 2015-early 2018), which showed a difference of 426 mm yr^{-1}, 124 mm yr^{-1}, 116 mm yr^{-1}, and 63 mm yr^{-1} from their means at the Berg reservoir, Waterskloof Reservoir, Wemmershoek Reservoir, and 5 km from the Eerst River site, respectively. However, using trends as a basis for the variability in annual *P* is not sufficient enough, and a stationarity test (Sun et al., 2018), is needed to examine climatic variability.

Autocorrelation of the time series for lags from 0 to 37 years for *P* at the Waterskloof Reservoir (Fig 6A) are estimated. 95% confidence intervals for autocorrelation (=$\pm\sqrt{\frac{1.96}{37}}$) are ±0.044. Results displays that majority of the lags that are ≥1, are statistically distinguishable

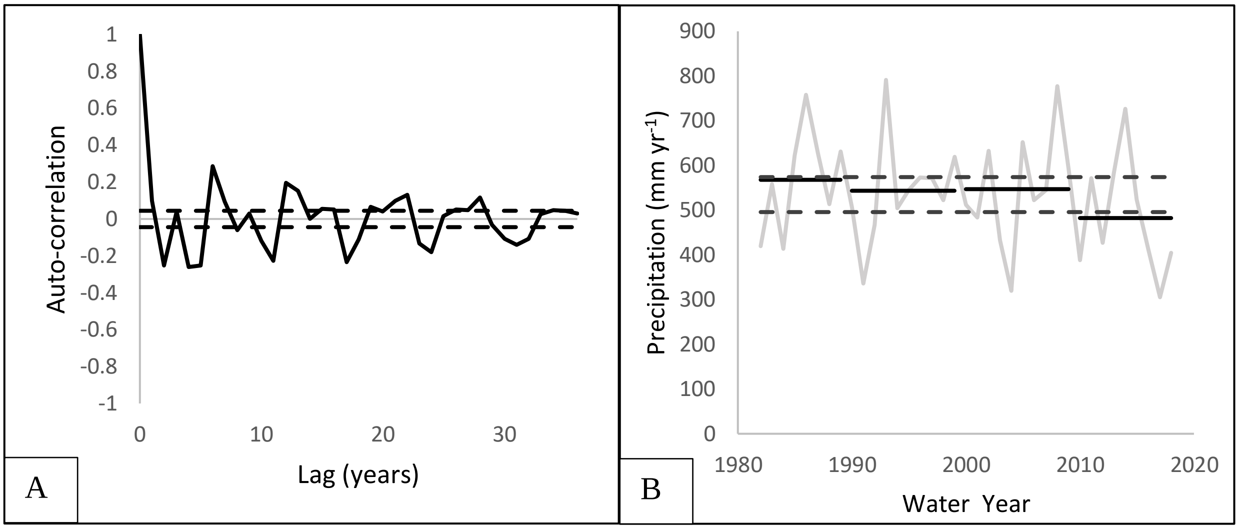


Figure 6 *Waterskloof Reservoir P. (A) Autocorrelation of P with 95% CI (dashed). (B) Averages over 10-year time periods with 95% CI (dashed).*

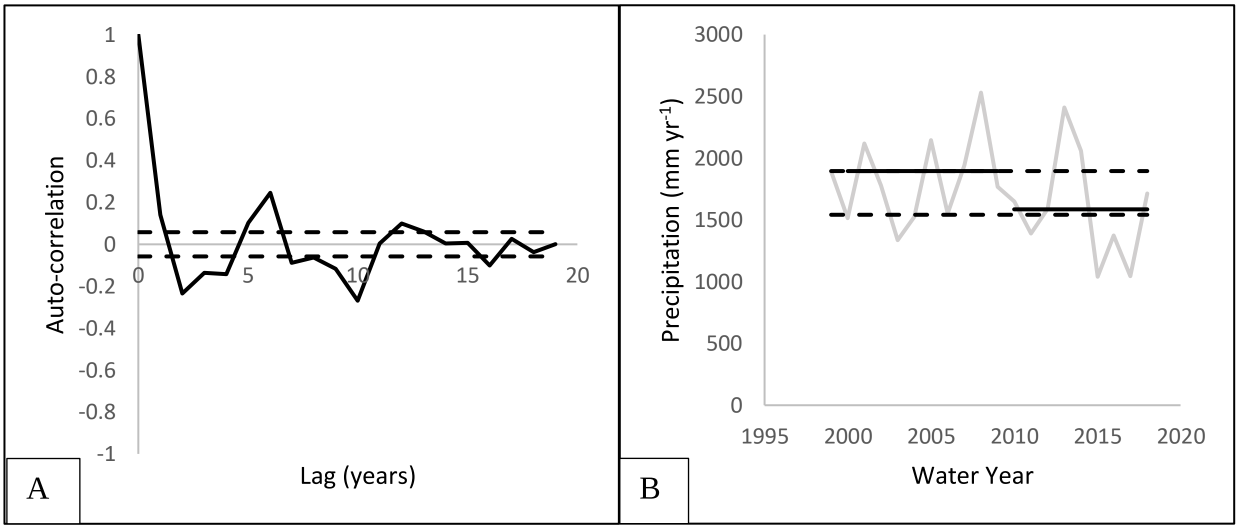


Figure 7 *Berg Reservoir P. (A) Autocorrelation of P with 95% CI (dashed). (B) Averages over 10-year time periods with 95% CI (dashed).*

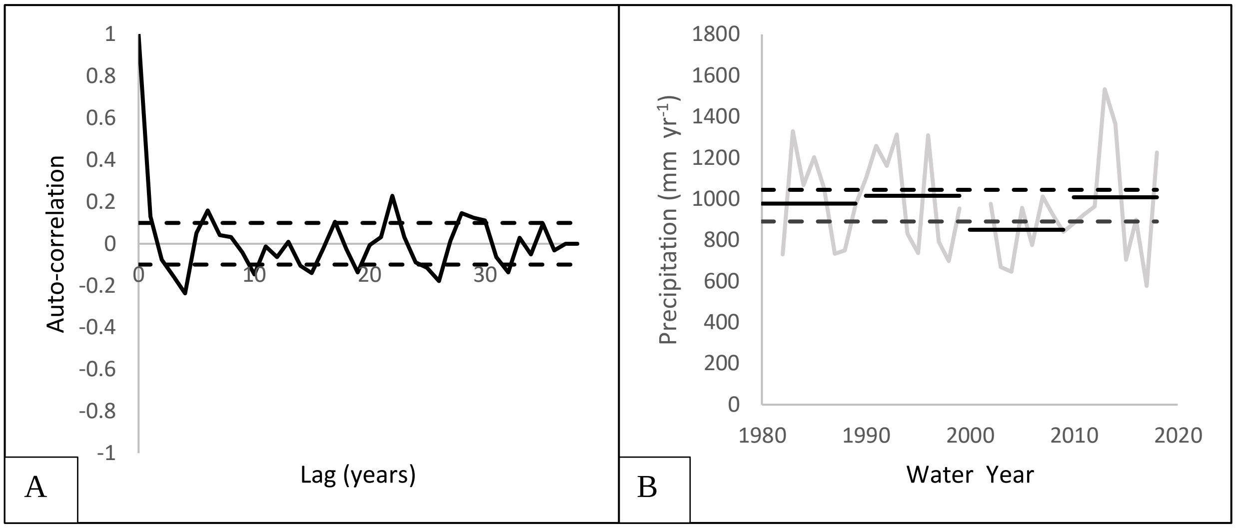


Figure 8 *Wemmershoek Reservoir P. (A) Autocorrelation of P with 95% CI (dashed). (B) Averages over 10-year time periods with 95% CI (dashed).*

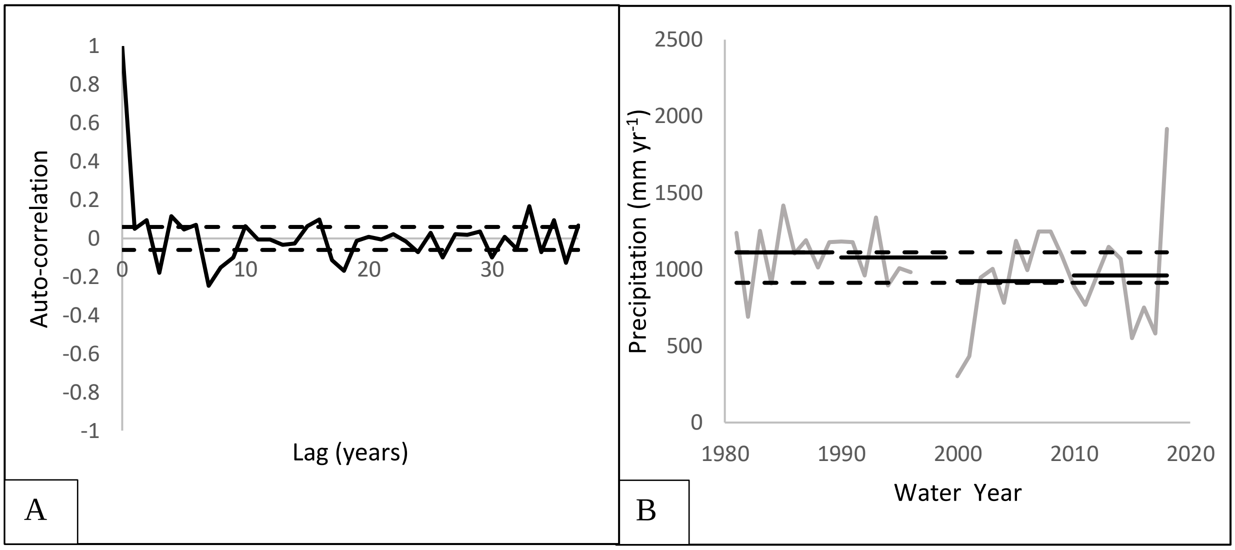


Figure 9 *Eerst River P. (A) Autocorrelation of P with 95% CI (dashed). (B) Averages over 10-year time periods with 95% CI (dashed).*

from 0. The variance (σ^2) of the entire 37-year time series is 14,334 (mm yr^{-1})^2, and the mean is 535 mm yr^{-1}. The standard error (SE) of the 37-year mean, ($\sqrt{\frac{\sigma^2}{n}}$) is 19.7 mm yr^{-1} and 10-year averages is 21.9 mm yr^{-1}. Calculating the averages of a 10-year period (Figure 6B), results show the averages do change each period, with three averages remaining within the boundary of the 95% interval and one 10-year period, the particularly dry/wet period (WYs 2010-2018), falling outside the boundary. The 95% confidence intervals for the 10-year averages (±39.1mm yr^{-1}) of the variation is 7.3% of the long-term mean.

For *P* at the Berg River reservoir, limits for autocorrelation (=± $\sqrt{\frac{1.64}{20}}$) are ±0.058 of the time for lags from 0 to 20 years (Figure 7A). Results display that the lags $\geq$1, are statistically distinguishable from 0. The variance (σ^2) of the entire 20-year time series is 154,862 (mm yr^{-1})^2, and the mean is 1,718 mm yr^{-1}. The SE of the 20-year mean is 88 mm yr^{-1} and 10-year average is 124.4 mm yr^{-1}. The 95% confidence intervals for the 10-year averages (±177 mm yr^{-1}) of the variation is 10.3% of the long-term mean. Results show both 10-year averages fall within the 95% bounds (Figure 7B).

For *P* at the Wemmershoek reservoir limits for autocorrelation, are (=± $\sqrt{\frac{1.96}{36}}$) are ±0.099 of the time for lags from 0-36 years (Figure 8A). Results display that a majority of the lags that are ≥1, are statistically indistinguishable from 0. The variance (σ^2) of the entire 36-year time series is 53,944 (mm yr^{-1})^2, and the mean is 967 mm yr^{-1}. The SE of the 36-yr mean is 38.7 mm yr^{-1} and 10-year average is 73.43 mm yr^{-1}. The 95% confidence intervals for the 10-year averages (±76.9 mm yr^{-1}) of the variation is 8% of the long-term mean. Results show three averages falling within the 95% bounds and one outside (WYs 2000-2010) (Figure 8B).

For *P* at the undammed Eerst river (=± $\sqrt{\frac{1.64}{38}}$) are ±0.060 of the time for lags from 0-38 years (Figure 9A). Results display majority of the lags are ≥1, are statistically distinguishable from 0. The variance (σ^2) of the entire 38-year time series is 80, 626 (mm yr^{-1})^2, and the mean is 1012 mm yr^{-1}. The SE of the 38-yr mean is 46.06 mm yr^{-1} and 10-year average is 89.79 mm yr^{-1}. Results show all four averages falling within the intervals (Figure 9B). The 95% confidence intervals for the 10-year averages (±99.5 mm yr^{-1}) of the variation is 9.9% of the long-term mean.

In summary, of the long-term gauged annual-*P* records at each site, all sites show different precipitation levels no matter the proximity to one another due to the spatial heterogeneity in precipitation. Annual-*P* varies year-year significantly for the most part, and although the 10-year averages change from one decade to the next, the overall annual-*P* time series remains stationary as only 2 of the 10-year averages fall outside the 95% CI and the overall long-term trends do not vary significantly.

Annual Runoff

Annual runoff was calculated for each gauged site from *Q* (Figure 10). This study focuses primarily on the most recent decade as all the time series overlaps in this period, but this plot shows how each site has changed over time in its full recorded time series. The Sonderend River at the beginning of its recorded period had higher runoff values than its most recent values and has shown a steady decline in runoff, which is further analyzed in the *Annual Water Balance* section. MAR for each site is observed in the *MAR Analysis* section. The undammed Onrus River does show the highest runoff values over the 2000-2010 decade.

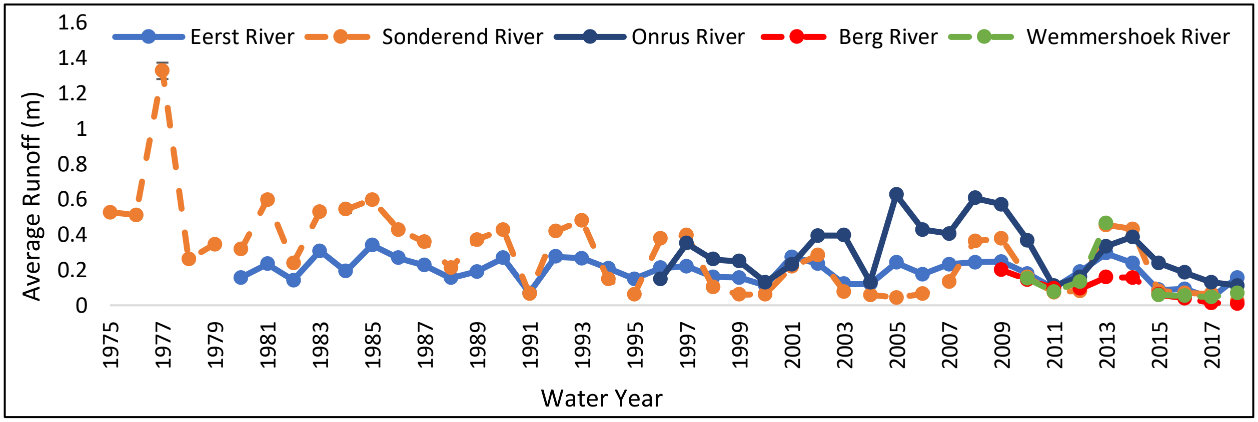


Figure 10 *Annual runoff from gauge data at stream sites on dammed rivers (dashed) and undammed rivers (solid).*

Table 3: Trend lines of annual runoff at all gauged sites with overlapping time series

WY	**Trend line (dammed)**	**Trend line (undammed)**
2010	y=0.007ln(x)+0.117	y=-0.09ln(x)+0.650
2011	y=0.009ln(x)+0.129	y=-0.006ln(x)+0.126
2012	y=0.015ln(x)+0.181	y=-0.153ln(x)+0.113
2013	y=0.268	y=0.340
2015	y=0.013ln(x)	y=-0.074ln(x)+0.471
2016	y=0.015ln(x)-0.022	y=-0.044ln(x)+0.323
2017	y=0.023ln(x)-0.077	y=-0.043ln(x)+0.263
2018	y=0.002ln(x)+0.221	y=0.1402

Annual runoff was also compared against catchment area among dammed and undammed rivers (Figure 11) in which each year's trend can be viewed in Table 3. The large, undammed watersheds are in more arid regions and runoff volume decreases with basin area. Essentially, the variations in precipitation (which are profound) and basin area complicate simple interpretations of this graph into dammed and undammed responses. Additional data are needed to examine more carefully paired watersheds (of which there are few) and to use flow duration analysis to examine inter-annual variations- essentially comparing each site with itself over wet and dry seasons. What is most apparent is that these scale variations appeared more apparent for the dammed rivers. Inter-annual variations were also higher for the dammed rivers than the undammed rivers, a trend much more visible in the flow duration analysis.

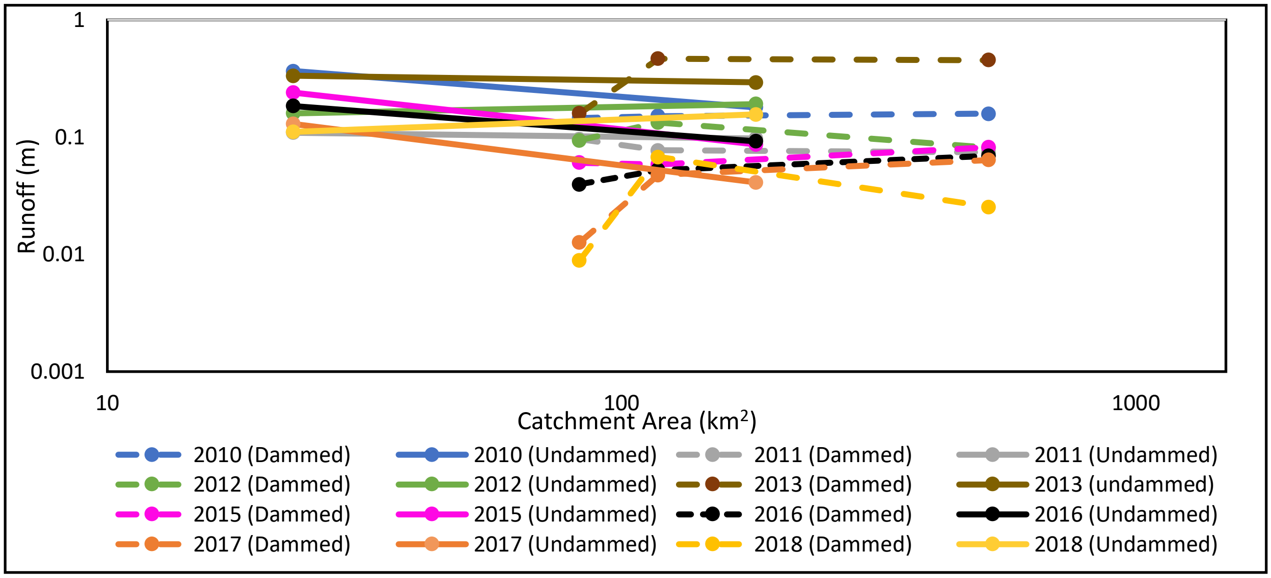


Figure 11 *Runoff relative to catchment area for dammed (dashed) and undammed (solid) sites.*

MAR Analysis

The smallest paired sites display the undammed river having larger MAR values than its paired dammed river (Figure 12A). The moderately size paired sites (for this study), contrastingly, display the dammed river having slightly larger runoff than its undammed river, but overall, on average, the undammed rivers do have greater MAR values than its paired dammed rivers over its overlapping period of recorded data (Figure 12B).

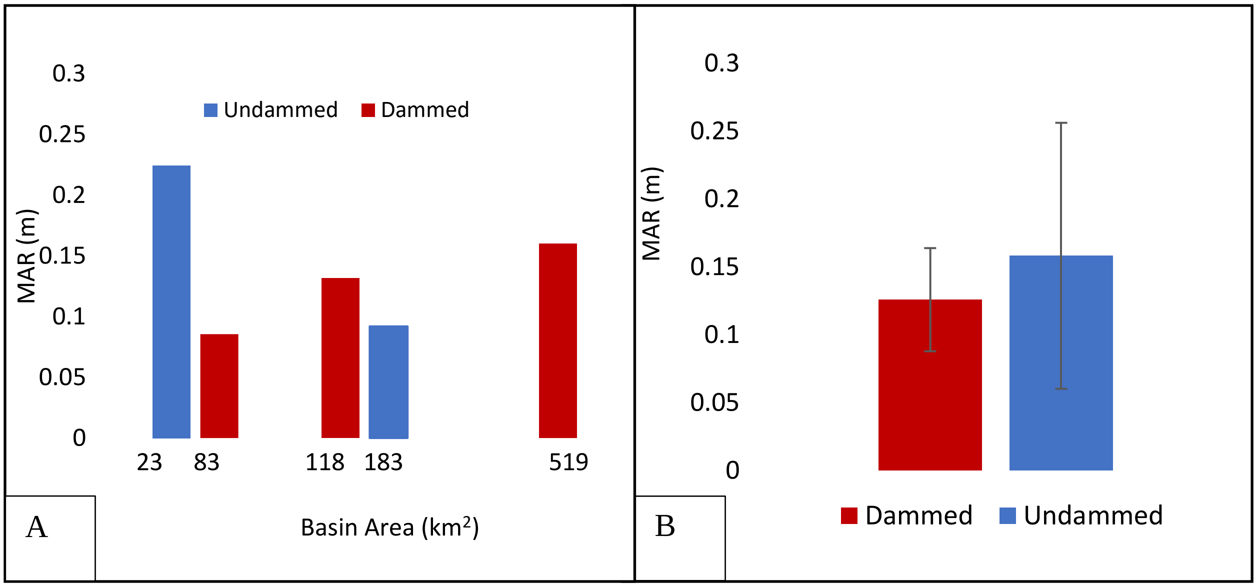


Figure 12 *MAR analysis from WYs 2010-2018 on each separate paired site (A) and (B) averaged out (excluding unpaired site). Error bars signify standard deviations of MAR values.*

Flow Duration Analysis (mean)

Flow duration analysis, the exceedance probability of daily discharge, has been analyzed for each of the gauging stations from WYs 2010-2018 (Figure 13). Both paired sites show the undammed rivers generally having greater flow throughout majority of the recorded period of time. The Wemmershoek river does indicate slightly larger sustained lower flows than the Eerst River and a slightly larger peak flow. The Berg river has reduced flows the entire period when compared to the Onrus River where its peak flow is over 4 times greater. A summary of all mean exceedance probability values is shown in Table 4 and graphically on an annual basis (Figure 14). However, the differences do not show a large amount of variability and are only averages

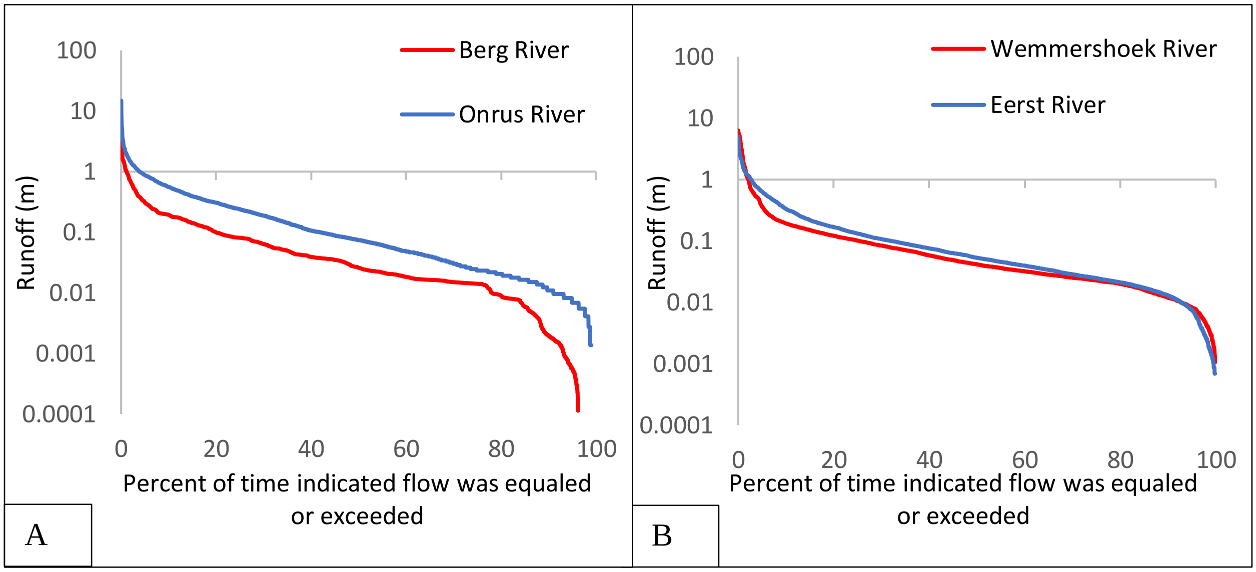


Figure 13 *Average Runoff Duration Curves of dammed (red) and undammed (blue) rivers between (A) smaller paired sites and (B) moderate sized paired sites.*

and therefore year by year analysis has been performed for each site to determine their variability.

Table 4: Mean exceedance probabilities of Q

Name	Onrus	Berg	Wemmershoek	Eerst	Sonderend
Q_{10} (m)	0.52	0.19	0.29	0.33	0.43
Q_{25} (m)	0.31	0.08	0.10	0.14	0.17
Q_{50} (m)	0.08	0.03	0.04	0.06	0.09
Q_{90} (m)	0.02	0.01	0.02	0.02	0.00
Peak flow (m)	14.78	3.44	6.32	5.00	102.23
Lowest flow (m)	0.00	0.00	0.00	0.00	0.00

***Q_x= runoff where x is percent of time flow was equaled or exceeded in recorded period**

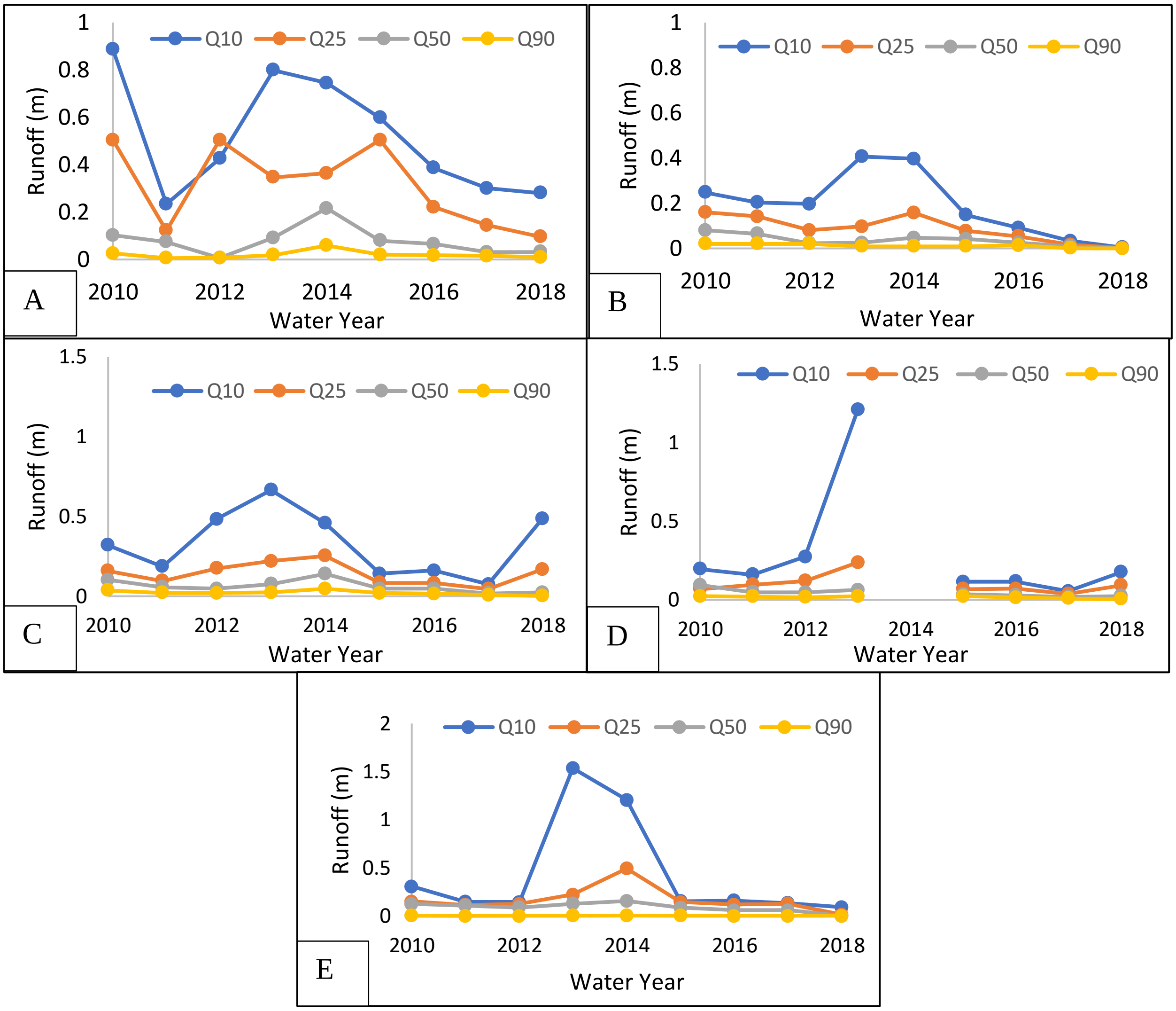
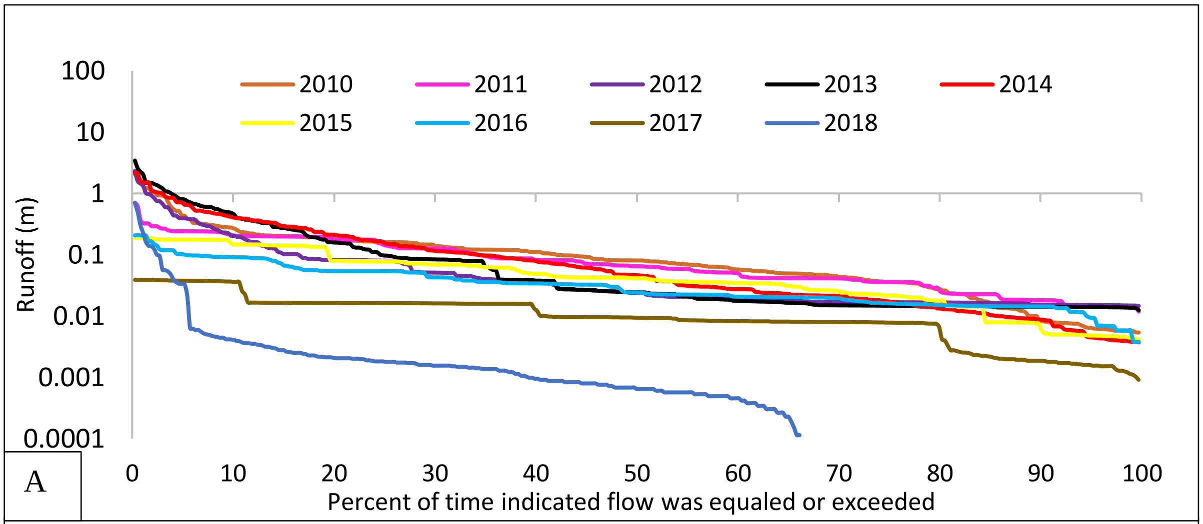
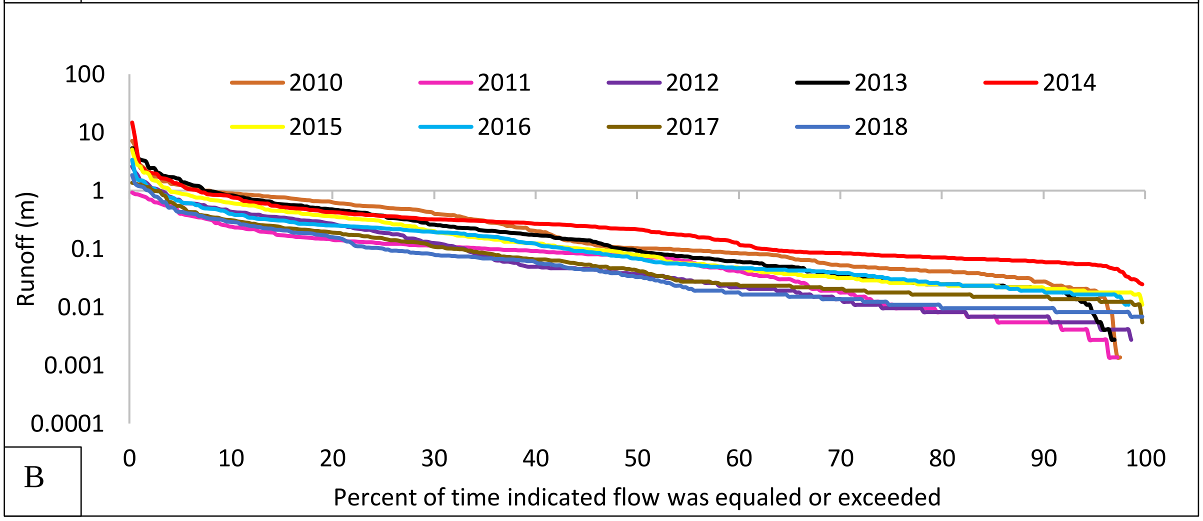


Figure 14 Annual exceedance probability of (A) Onrus River, (B) Berg River, (C) Eerst River, (D) Wemmershoek River, and (E) Sonderend River.

Flow Duration Analysis (inter-annual)

Inter-annual flow duration curves for each site (Figure 15A, 15B, 15C, 15D, 15E), show that the Berg River has a greater amount of inter-annual variability compared to the undammed Onrus River. The variability and reduced runoff is most evident in the drought years, where WY 2017 and 2018 show rapid changes in flow that are not present in the Onrus River. Over 30% of the time in WY 2018, the river has no runoff, with the peak flow 40 times greater than its lowest flow. When observing the Eerst and Wemmerhsoek river flow duration curves on an annual basis, both sites appear to have much more similar variability. The driest year shows more variability in the undammed river in this case. The inter-annual variability is most apparent in the Sonderend River where there is a 50-fold flow change in its driest WY in 2018, where at one point it only took 10% of the time for the river's flow to drop 20x the magnitude. Almost every year contains similar rapid changes in flow regardless of it being a wet or dry year.





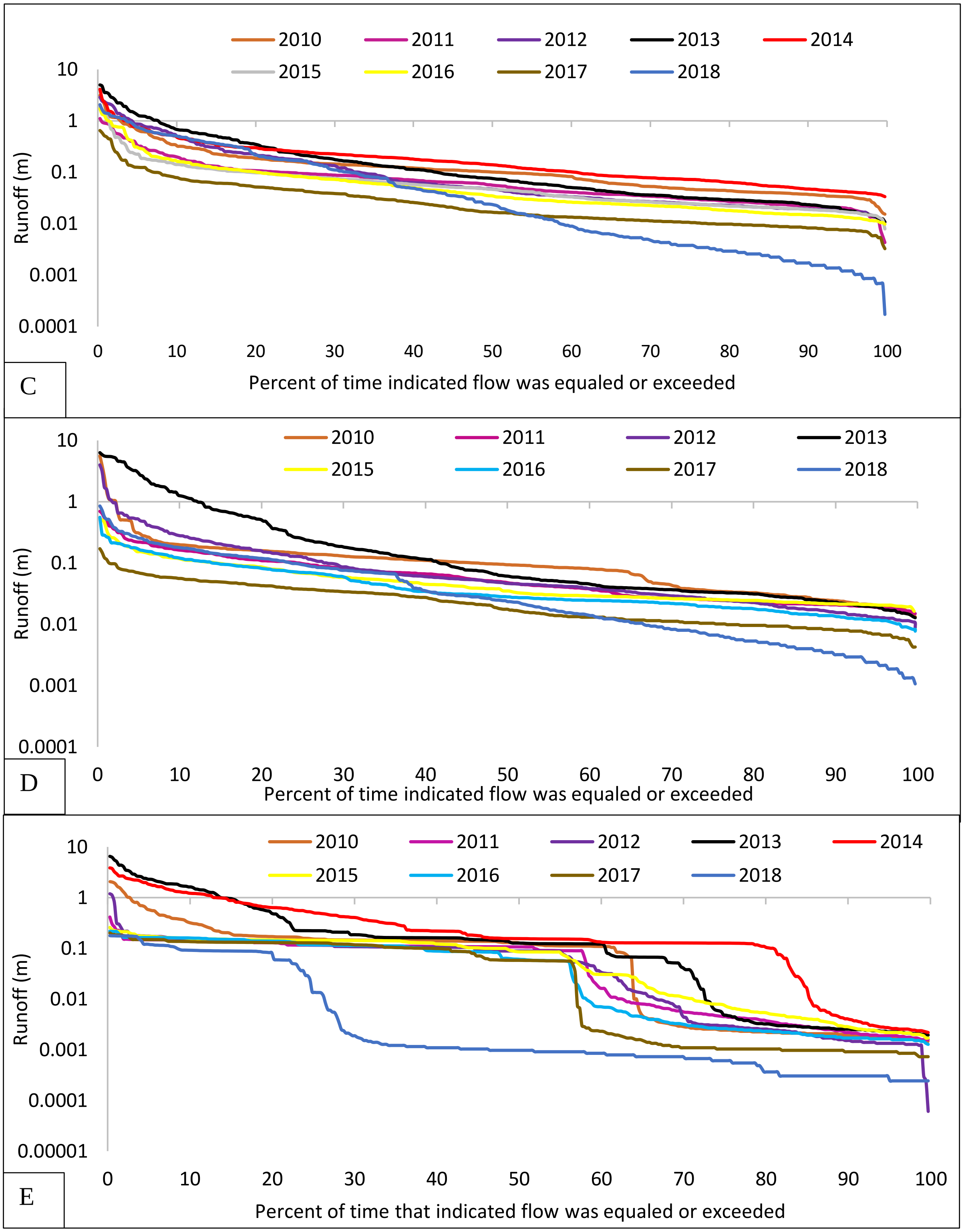


Figure 15 *Runoff duration curve from 2010-2018 of (A) Dammed Berg River, (B) Undammed Onrus River, (C) Dammed Wemmershoek River, (D) Undammed Eerst River, and (E) Dammed Sonderend River.*

Wetted Width

Figure 16 shows where wetted width measurements were recorded. Wetted channel width was obtained from multiple measurements from dated air photos. Photo dates selected for width measurement were: 01/17/10, 01/28/12, 12/26/13, 10/13/14, 04/19/15, 02/16/16, 01/25/17/, 03/24/17, and 04/22/17. The daily average discharge for each date was then obtained from the gauging record. Data suggests Q is directly related to wetted width on the Berg River (Figure 16). Due to width being a linear function of discharge, the probability of wetted widths were evaluated for this river for various time periods (comparing wet and dry years). These wetted width probability distributions were used to evaluate the impact of reservoirs on stream habitat.

Figure 16 *Site along Berg River where wetted width measurements were taken in (A) Wet Year and (B) Dry Year. Yellow lines represent wetted width. The site is approximately 0.65 km downstream the Berg River Dam.*

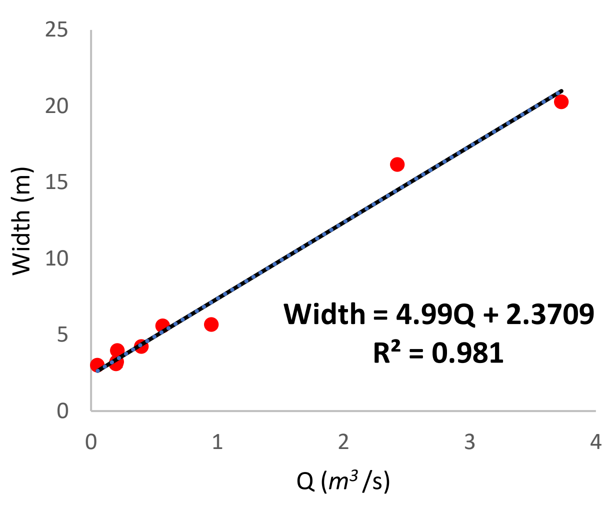


Figure 17 *Wetted width and discharge measurements at gauged site on Berg River. Error bars represent standard deviations from different trials.*

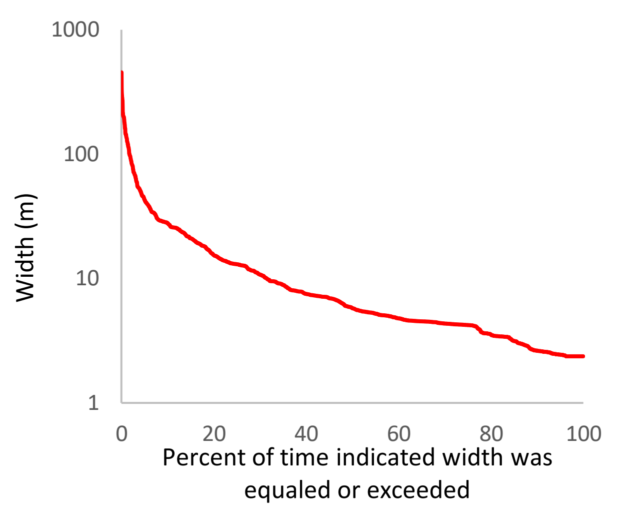


Figure 18 *Width Exceedance Probability of Berg River.*

Similar to daily runoff, wetted width exhibited significant inter-annual and within year variability, with reduced width during dry years and seasons. The Berg river had a peak width of around 455 m and its lowest width at under 3 m. (Figure 18). This only shows a long-term trend in width and the variability on an inter-annual basis (Figure 19) show significant variability with rapid changes in width, like *Q*, being apparent in the Berg River. WY 2013, the wettest year, had around a 115-fold change in its width values from peak to lowest width. The sudden changes in width are also most evident in the driest years.

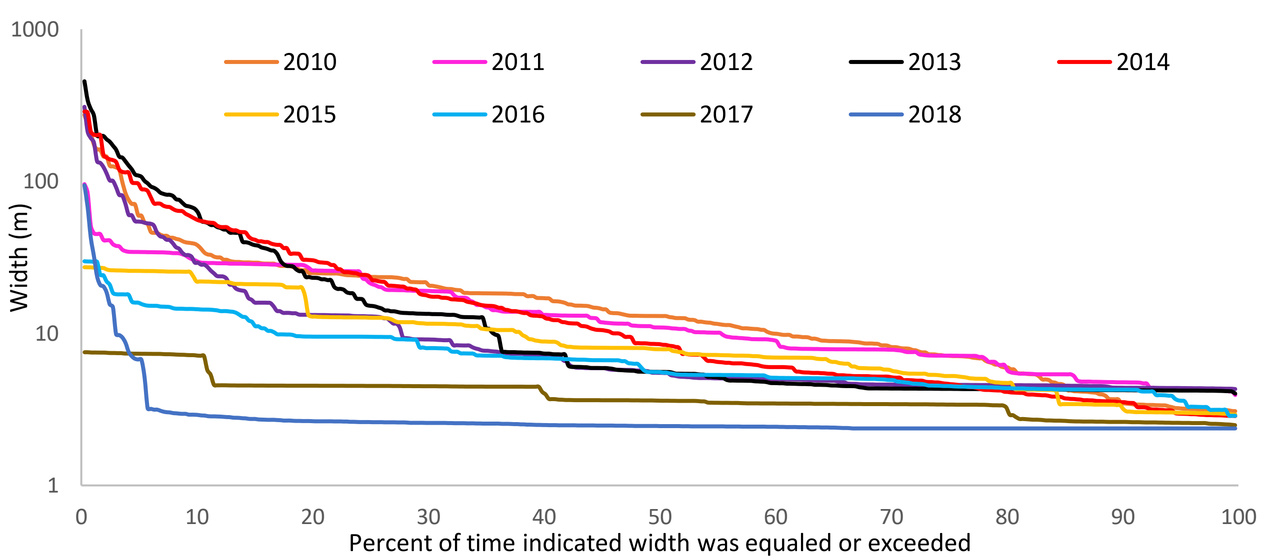


Figure 19 *Inter-annual width exceedance probability of Berg River.*

Annual Water Balance

The Sonderend River is the most ideal of the dammed rivers to compute rainfall-runoff relationships due its long-recorded period of available data. Runoff has been declining since the construction period of the dam, precipitation has been relatively constant during this time interval and ET has been increasing since as well (Figure 20). Between the Eerst and Wemmerhshoek river (Figure 15), ET is around 46 mm greater in the Wemmershoek River.

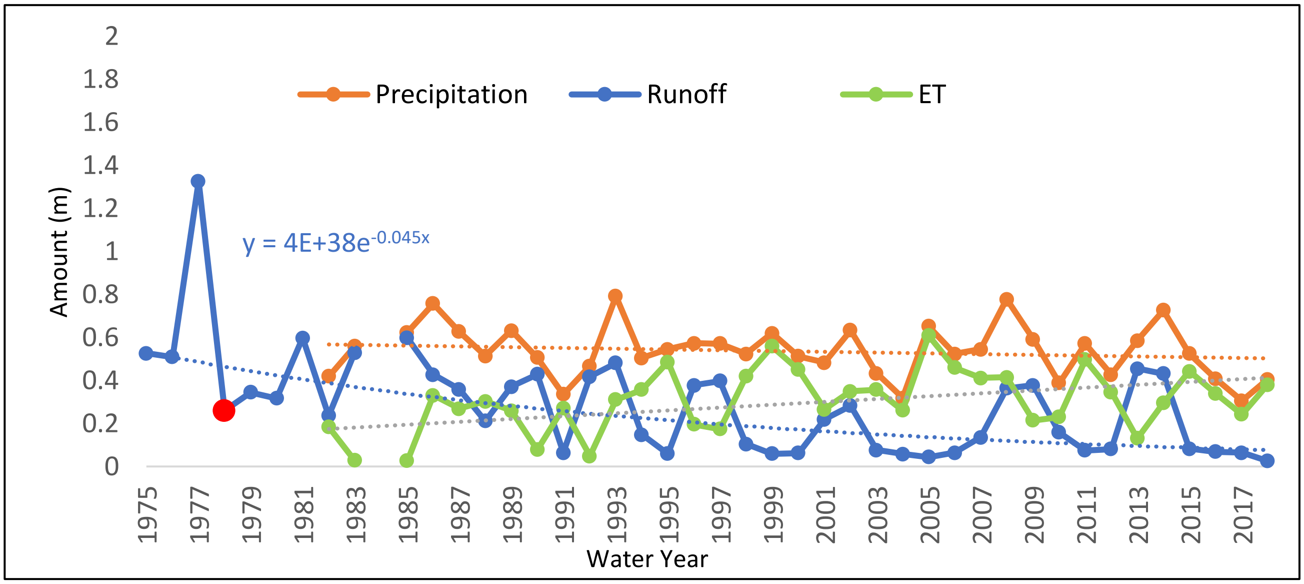


Figure 20 *Water balance relationships on Sonderend River with long term trends (dashed). Red marker represents when the Waterskloof dam was opened.*

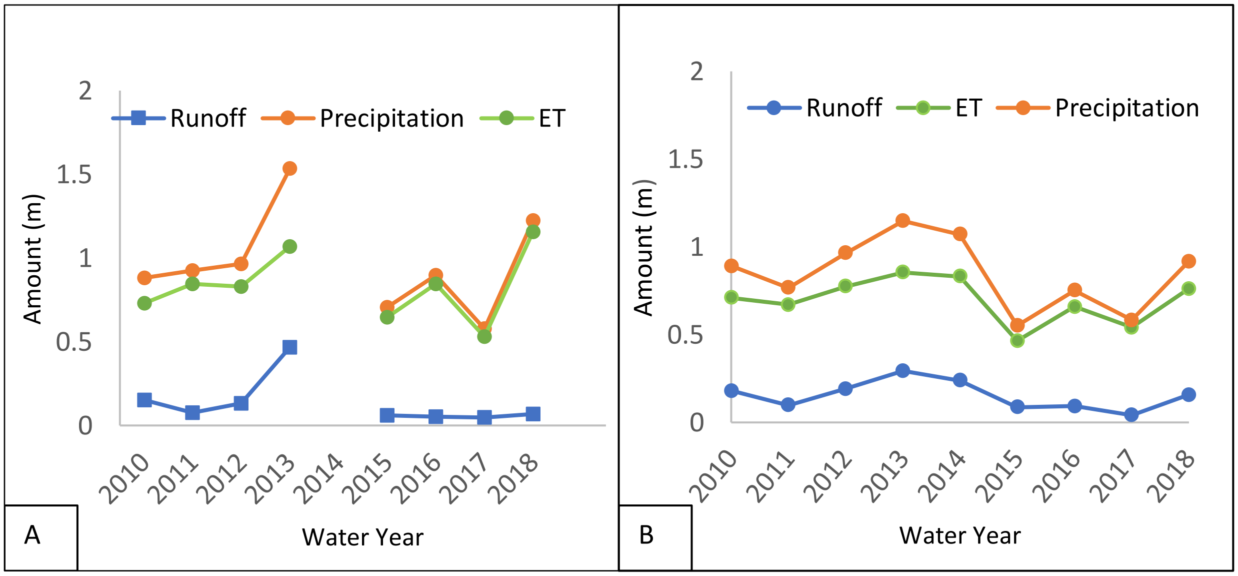


Figure 21 *Water Balance relationships on (A) Wemmershoek River and (B) Eerst River.*

Summary Tables

Table 5 details all water balance calculated values using the procedures described above. These calculations were made in order to compare how dammed and undammed rivers in Western Cape behave differently. These are useful in distinguishing different relationships described previously.

Table 5: Summary of precipitation, runoff, and water use for dammed and undammed rivers (WYs 2010-2018).

Name	Onrus	Berg	Wemmershoek	Eerst	Sonderend
Status	free	reservoir	reservoir	free	reservoir
Area (km$_2$)	23	83	118	183	519
MAP (mm)	-	1586	1008	983	494
MAP CV	-	0.28	0.31	0.26	0.27
MAR (mm)	224	86	132	153	160
MAR CV	0.50	0.69	1.07	0.53	1.02
MAR (%of MAP)	-	5.4	13.1	15.6	32.4
ET (mm)+MWUse	-	1500	876	830	334

MAP=Mean Annual Precipitation, CV=Coefficient of Variation, ET=Evapotranspiration (MAP-MAR)

Discussion

The present study investigated the impacts of dams on water quantity of 3/6 of the major dams part of the WCWSS using data available from national databases. Runoff and *Q* data does support the hypothesis (H_1) that reservoir storage causes significantly reduced river discharge (*Q*) and annual runoff compared to similar undammed rivers, most evident in dry years but for different levels of flow. For the smallest sized catchment area sites, the results of the MAR comparisons in the last decade indicate that the dammed site (Berg River) has smaller MAR values than its paired undammed river (Onrus River). Flow duration analysis results indicate that the undammed river sustains higher flows during its entire recorded period on all flow levels (high, moderate, and low flows) and shows smaller inter-annual variability with an absence of significant reductions in flow that is apparent in the dammed river.

For the medium sized area sites, the results of the MAR comparison in the last decade indicate that the dammed site (Wemmershoek River) contrastingly has larger MAR values than its paired undammed river (Eerst River). However, flow duration analysis indicate that the undammed river sustains higher flows during a portion of its recorded period (moderate flows), while the lower flows and peak flows are slighter greater than the undammed river. On an inter-annual basis, they show much more similar inter-annual variability than the other paired sites.

Annual Water Balance indicates that ET is increasing at both sites, with the dammed site having greater mean ET. Runoff values also appeared to follow the trend of precipitation much more similar than in the dammed river. This is likely due to the unimpeding of flow in undammed rivers. Reasons as to why the Wemmershoek and Eerst river showed more similar inter-annual variability, remains unclear. With an absence of water use data, it is difficult to determine where the runoff is going besides through ET, but it is likely that less water is taken from this reservoir as compared to the Berg Reservoir or that water is being taken from the undammed Eerst river for agricultural or urban use.

The Waterskloof Reservoir, the largest of the sites compared to itself, had inter-annual flow duration analysis results indicating the largest changes in flow of any of the sites. Runoff shows a declining trend since its construction period and ET appears to be increasing like the other dammed site.

The dammed Berg River exhibited a simple relationship between wetted width and discharge. These data indicate significant reduction in river or floodplain width during dry years and dry seasons, as predicted by the flow duration analysis, thus supporting the hypothesis that reservoir storage shifts the probability distribution of wetted widths towards smaller widths and causes greater inter-annual variability in riparian water supply (H_2). However, future work would involve obtaining width data for all the sites, so a quantifiable comparison of width can be made among undammed rivers.

When linking annual-*P* to runoff, sometimes the rapid variations are not as evident in annual-*P* as much as they are in annual runoff. The sudden rapid changes in flow seen in 2/3 of the dammed sites, are likely due to the releasing of water during wet years or trapping of water during dry years. The largest changes were apparent downstream the Waterskloof Dam. The data suggest that some of the dammed rivers had significant periods of no or very low flow during dry years. Although the variations in lower flows do indicate small variations in the total runoff, this is still very important as these periods of flow might kill all aquatic life in the region. The actual change in runoff might be small but small amounts of flow might be sufficient enough to allow aquatic life to survive during dry periods.

Annual precipitation data does not support the hypothesis, that precipitation has changed significantly over the past 40 years (H_3) and climate change in this region. Precipitation was spatially heterogeneous, causing statistically significant year-to-year variations in all sites, and a few longer variations apparent at different sites. However, overall, majority of decadal averages in precipitation over the past 40 years were insignificant, implying nonstationary behavior, except in 2 decades at 2/4 of the sites; WYs (2000-2010) at the Berg River reservoir and WYs (2010-2018) at the Waterskloof Dam. WYs 2000-2010 contained another very dry period, which appeared to have the most impact where the Berg Reservoir was. WYs 2010-2018, contained the driest period in all 40 years of the time series, but in addition contained one of the wettest years prior to the drought, WY 2013. This goes to show that availability of water is becoming increasingly unpredictable with climate change. The balance between the very wet year and successive dry years is what made the other precipitation sites exemplify a stationary annual-*P* on a 10-year timescale. This decade had the clearest impact on the Waterskloof Reservoir, seen that it was the only site that showed nonstationary annual-*P*. This could imply that the water crisis that occurred during this decade may have not been entirely due to change in rainfall levels but may also have been heavily influenced by change in human consumption in all three reservoirs.

Human Consumption

Unfortunately, annual water consumption data was unavailable for each dam separately, however, dam storage relative to urban water use (Figure 22A) and agriculture water use (Figure 22B) data for the Big Six dams on average were available in the last decade. As expected, water use is directly related to change in dam storage and water use is almost always lower than the dam storage as it should be. However, during the major drought, human consumption both from urban and agricultural use actually exceeded the amount of water that was stored, implying that more water was being used than what was available. Another indication, that the cape town water crisis was not entirely due to the drought.

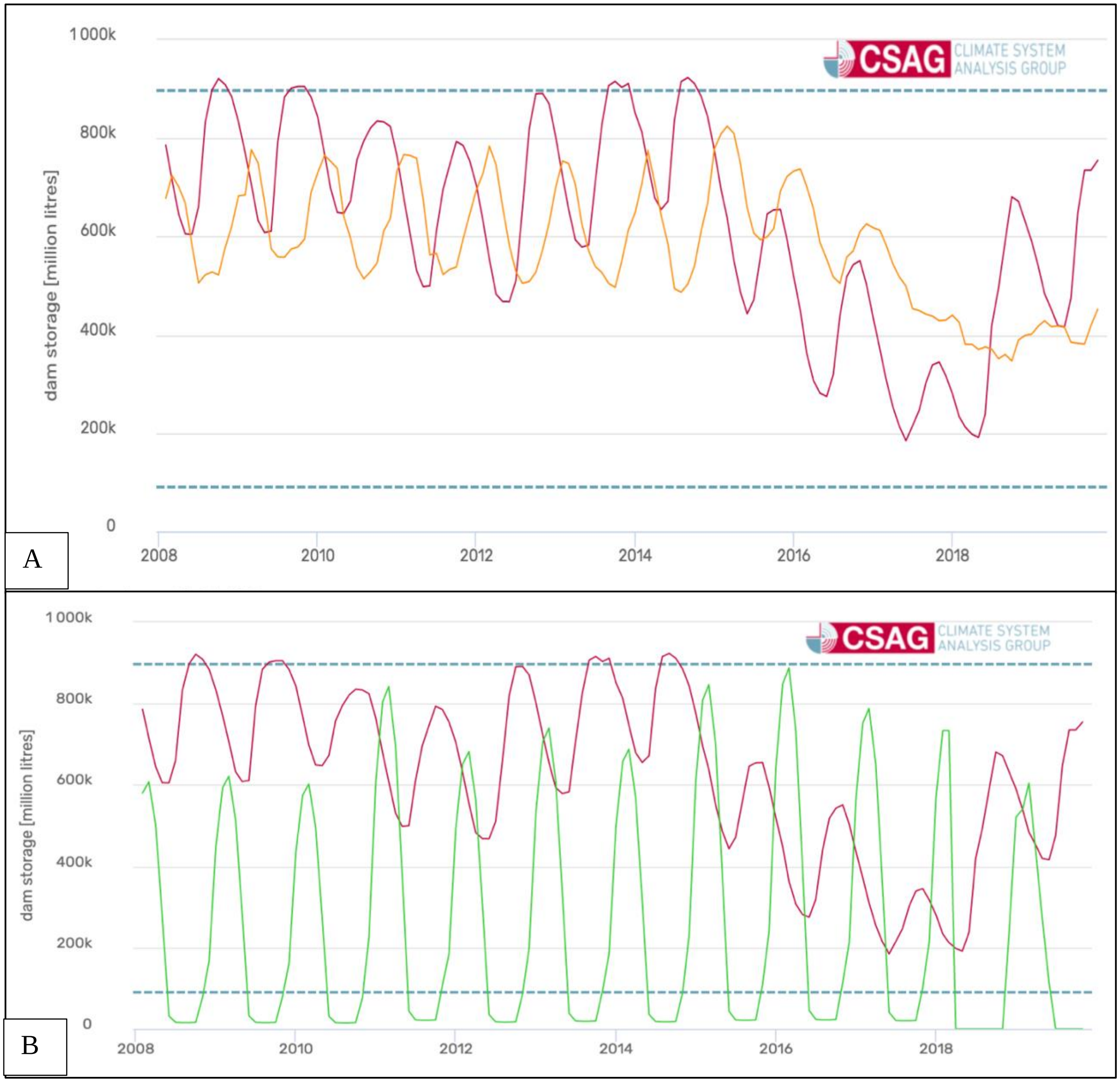


Figure 22 Dam storage (red) vs (A) Urban use (orange) and (B) Agriculture Use (green) from the Big Six dams (CSAG, 2019b).

Limitations

There are various imitations to the interpretations of these research results. Firstly, this study highlights the need for additional precipitation data to account for the spatial heterogeneity in precipitation. As mentioned, data at the Onrus river site were unavailable and data for the Eerst river were obtained 5 km from the actual site where flow data was taken. A 2nd limitation was that annual water use data for each dam separately were unavailable. The absence in precipitation data at the exact locations along with missing water use data made it very challenging to make precise water balance calculations for all sites.

Finally, none of the dams had recorded flow data prior to the construction of the dam, except partially for the Sonderend river, where data was recorded during the construction period of the upstream dam. This is very critical in explaining the full impact that dams have on flow regimes especially in an area that stores so many reservoirs. With an absence of pre-dam data, it is difficult to quantify how much the dam impacts the flow, as this study used a paired water approach instead. It is critical South African national databases be transparent and publish this data, so its environmental impacts can be quantified in terms of freshwater conservation policies and planning in South Africa.

Conclusions

This research has found some generalizations about how selected dammed rivers behave differently than undammed rivers in the Western Cape in terms of lower Mean Annual Runoffs, greater evapotranspiration levels and greater inter-annual variability. These findings support hypothesis 1 that reservoir storage causes significantly reduced river discharge and annual runoff compared to similar undammed rivers and supports hypothesis 2 that reservoir storage shifts the probability distribution of wetted widths towards smaller widths and causes greater inter-annual variability in riparian water supply. The data does not support hypothesis 3 of climate change in this region of annual precipitation changing significantly in the past 40 years,

With the observed increasing ET levels that were greatest in the dammed rivers, it is likely ET will continue to increase as the climate warms causing an increased frequency of major drought events similar to the 2015-2018 drought that led to a water crisis. Alternative sources of water, such as through desalinization, should be the priority solution to this, but with a rapidly growing population, it can be assumed more rivers will be dammed to meet the demand due to its current lower cost and less energy intensiveness of desalinization. If damming continues, it is strongly recommended that attempts be made to reduce ET through limiting reservoir exposure to the atmosphere. This can be done through various methods such as storing water underground, damming rivers in valleys as opposed to exposed planes, spreading surface films or floating solar arrays that would not only reduce ET but provide clean energy into the process additionally.

Thus, this research aims to provide insight into how human infrastructure plays a role on water quantity. Climate change is making water predictability incredibly challenging and regions where communities rely heavily on reservoir storage are at risk in times of drought. In a province so dependent on reservoir storage, studying the behavior of free flowing and regulated rivers is essential for planning for a changing climate and a growing population. As availability of water is becoming increasingly unpredictable with climate change, it is essential to understand how human infrastructure affects water quantity. With drought comes an increased pressure on water resources. Characterizing the impact of reservoirs on streamflow and stream habitat provides better understanding of the impacts of reservoir storage on Western Cape rivers.

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Honor Code

I pledge on my honor that I have not given or received any unauthorized assistance on this assignment/examination.

ANNUAL DISCHARGE (Q) (m3/s) (FROM DAILY Q DATA)

Water Year	Eerst (G2H020)	Waterskloof (H6H012)	Onrus (G4H033)	Berg (H6H077)	Wemmershoek (G1H080)
1975		8.654041096			
1976		8.385967213			
1977		21.82464658			
1978		4.280482192			
1979		5.670263014			
1980	0.905122951	5.219412568			
1981	1.360610959	9.836641096			
1982	0.817150685	3.891808219			
1983	1.780260274	8.707657534			
1984	1.113163934	8.929035821			
1985	1.976586301	9.827632877			
1986	1.547117647	7.027306849			
1987	1.308975342	5.898517808			
1988	0.895084699	3.465728767			
1989	1.1081875	6.107724044			
1990	1.555912329	7.039564384			
1991	0.39967033	1.055934247			
1992	1.591044199	6.869155738			
1993	1.539633117	7.9048			
1994	1.216831832	2.425690411			
1995	0.867849315	0.977432877			
1996	1.222166667	6.209142466	0.107046448		
1997	1.279633053	6.52836612	0.2562		
1998	0.92940274	1.711153425	0.189890411		
1999	0.90400274	0.986926027	0.182072131		
2000	0.652243169	1.026478142	0.094433234		
2001	1.588553425	3.591594521	0.1684081		
2002	1.371328767	4.662250814	0.287553425		
2003	0.701378082	1.268712329	0.288224658		
2004	0.698185792	0.953896175	0.095134247		
2005	1.398350685	0.720363388	0.456336986		
2006	1.018105263	1.058227397	0.311778082		
2007	1.347956164	2.214167123	0.296115068		
2008	1.415051913	5.972644809	0.442420765		
2009	1.433942466	6.202578082	0.41730137	5.249331507	
2010	1.03929589	2.610338369	0.267569863	3.826625352	0.564747945
2011	0.564580822	1.220835616	0.07950137	2.526586667	0.288978142
2012	1.109065574	1.33904918	0.116355191	2.474308743	0.498457534
2013	1.702764384	7.485742466	0.243920548	4.189580822	1.746158904
2014	1.383863014	7.109150685	0.281931507	4.092257534	
2015	0.502172603	1.346791781	0.175082192	1.590814404	0.218864
2016	0.533724044	1.139151685	0.134355191	1.04415847	0.196191257
2017	0.238136986	1.047819178	0.094553425	0.332698276	0.177561644
2018	0.907673973	0.416682192	0.08089863	0.23429863	0.253920548

RUNOFF (m) (calculated from Q)

Water Year	Eerst	Waterskloof	Onrus	Berg	Wemmershoek
1975		0.525912247			
1976		0.509621206			
1977		1.326299331			
1978		0.260127954			
1979		0.344585926			
1980	0.15599769	0.317187423			
1981	0.23450093	0.597779692			
1982	0.1408357	0.23650796			
1983	0.30682737	0.529170556			
1984	0.1918535	0.542623872			
1985	0.34066411	0.597232256			
1986	0.2666453	0.427054447			
1987	0.22560154	0.358457132			
1988	0.1542676	0.210614808			
1989	0.19099581	0.371170744			
1990	0.26816106	0.427799346			
1991	0.06888307	0.064169877			
1992	0.27421603	0.417443491			
1993	0.26535535	0.480380331			
1994	0.20972063	0.147410936			
1995	0.14957359	0.059399293			
1996	0.21064009	0.377334014	0.14660709		
1997	0.22054441	0.396733463	0.35088261		
1998	0.16018231	0.103988014	0.2600673		
1999	0.15580463	0.059976198	0.24935966		
2000	0.11241393	0.062379808	0.12933247		
2001	0.27378675	0.218263759	0.23064588		
2002	0.23634814	0.283328306	0.39382317		
2003	0.12088232	0.077100553	0.39474247		
2004	0.12033213	0.057968951	0.13029256		
2005	0.24100536	0.043776997	0.62498326		
2006	0.17547016	0.064309233	0.42700042		
2007	0.23231988	0.134556515	0.4055489		
2008	0.24388381	0.362961883	0.60592409		
2009	0.24713959	0.376935092	0.57152144	0.1994746	
2010	0.17912236	0.158632124	0.36645438	0.14541176	0.150758985
2011	0.09730535	0.074191051	0.10888231	0.09601029	0.07714247
2012	0.19114715	0.081374973	0.15935602	0.09402373	0.133062816
2013	0.29347098	0.454913906	0.3340651	0.15920407	0.46613564
2014	0.23850841	0.432028155	0.38612359	0.15550579	
2015	0.08654931	0.081845497	0.23978648	0.06045095	0.058425559
2016	0.09198719	0.06922706	0.1840082	0.03967802	0.05237309
2017	0.04104284	0.063676718	0.12949708	0.01264253	0.04739993
2018	0.15643736	0.025322074	0.11079595	0.00890335	0.067783875

PRECIPITATION (mm)

Water Year	Wemmershoek	Waterskloof	Eerst (5km from Q site)	Berg
1980	964.1			
1981			1240.9	
1982	729.199	419.1999	690.3	
1983	1330.4999	558.2	1252	
1984	1065.7991	414.1991	908.6	
1985	1203.3999	623.0001	1416.7	
1986	1051.19991	757.8	1104.1	
1987	733.4001	626.5	1191.1	
1988	749.7	513.4	1014.2	
1989	969.0999	631	1179.2	
1990	1102.5981	506.1	1182.4	
1991	1257.0001	336	1178.3	
1992	1160.699	466.6	960.9	
1993	1312.0009	791.3	1338.8	
1994	830.8	503.8	896.3	
1995	737.9	544.9	1007.1	
1996	1310.1	572.5	982.2	
1997	792.099	571.09		
1998	697.99899	523.11		
1999	952.3001	618.99		1889.3
2000		512.5991	302.9	1513.2
2001		483.2	431.6	2120.3
2002	976.4	632.501	946.8	1779
2003	669.9	433.699	1004.8	1333.9
2004	646.8	319.001	783.2	1527.1
2005	956.499	652.1	1188	2145.4
2006	775.8001	523.099	994.4	1550.4
2007	1011.9	545.498	1248.8	1943
2008	925.8	777.501	1246.5	2530
2009	838.9	591.4	1086.1	1767
2010	881.899	388.7	890.2	1651
2011	923.8809	571.09	767.2	1391.6
2012	963.2999	427.209	965.8	1589.6
2013	1533.6009	584.8	1.15E+03	2.41E+03
2014	1364.6	7.26E+02	1070.9	2057.8
2015	705.2	524.299	551.2	1039.9
2016	899.098	408.8709	751.8	1371.5
2017	577.1009	305.3301	582.6	1045
2018	1225.3	405.1299	917.3	1714.5

WETTED WIDTH (m)

Date	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
1/17/10	3.08	4.71	4.79	4.78	4.67
1/28/12	4.23	5.54	5.49	5.3	5.39
12/26/13	5.55	5.67	5.71	5.74	5.37
10/13/14	5.66	6.09	5.89	5.96	6
4/19/15	20.25	21.65	22.62	22.08	21.06
2/16/16	16.16	11.29	11.51	11.25	11.31
1/25/17	2.98	3.49	3.27	3.29	3.56
3/24/17	3.94	4.1	4.2	4.45	4.3
4/22/17	3.21	4.97	4.8	4.5	4.67