FLOW REGIME ALTERATIONS UNDER CHANGING CLIMATE IN TWO RIVER BASINS: IMPLICATIONS FOR FRESHWATER ECOSYSTEMS

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ABSTRACT

We examined impacts of future climate scenarios on flow regimes and how predicted changes might affect river ecosystems. We examined two case studies: Cle Elum River, Washington, and Chattahoochee–Apalachicola River Basin, Georgia and Florida. These rivers had available downscaled global circulation model (GCM) data and allowed us to analyse the effects of future climate scenarios on rivers with (1) different hydrographs, (2) high future water demands, and (3) a river–floodplain system. We compared observed flow regimes to those predicted under future climate scenarios to describe the extent and type of changes predicted to occur. Daily stream flow under future climate scenarios was created by either statistically downscaling GCMs (Cle Elum) or creating a regression model between climatological parameters predicted from GCMs and stream flow (Chattahoochee–Apalachicola). Flow regimes were examined for changes from current conditions with respect to ecologically relevant features including the magnitude and timing of minimum and maximum flows. The Cle Elum's hydrograph under future climate scenarios showed a dramatic shift in the timing of peak flows and lower low flow of a longer duration. These changes could mean higher summer water temperatures, lower summer dissolved oxygen, and reduced survival of larval fishes. The Chattahoochee–Apalachicola basin is heavily impacted by dams and water withdrawals for human consumption; therefore, we made comparisons between pre-large dam conditions, current conditions, current conditions with future demand, and future climate scenarios with future demand to separate climate change effects and other anthropogenic impacts. Dam construction, future climate, and future demand decreased the flow variability of the river. In addition, minimum flows were lower under future climate scenarios. These changes could decrease the connectivity of the channel and the floodplain, decrease habitat availability, and potentially lower the ability of the river to assimilate wastewater treatment plant effluent. Our study illustrates the types of changes that river ecosystems might experience under future climates. Copyright © 2005 John Wiley & Sons, Ltd.

INTRODUCTION

The quantity and timing of river flow are critical components to water supply, water quality, and the ecological integrity of river systems (Poff *et al.*, 1997). The five components of flow regime (magnitude, frequency, duration, timing and rate of change) influence the ecological dynamics of river systems directly and indirectly through their effects on other primary regulators (Karr, 1991; Poff *et al.*, 1997). Alteration of any of these flow parameters can have dramatic effects on aquatic organisms, riparian species, energy flow in the system, sediment movement and floodplain interactions (Poff *et al.*, 1997, and references therein). Hence, climatic changes that create shifts in the timing and magnitude of low or high flow events or change the magnitude of river flow at monthly, seasonal, or yearly time scales could result in dramatically altered river systems.

There have been numerous studies that have examined the potential impacts of future climate scenarios on aquatic ecosystems at a regional scale (e.g. Hauer *et al.*, 1997; Melack *et al.*, 1997; Moore *et al.*, 1997; Mulholland *et al.*, 1997; Meyer *et al.*, 1999; Stone *et al.*, 2001). These studies give insight to the type of changes that might be expected for aquatic ecosystems and their inhabitants under future climate scenarios, including changes in species

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ranges, nutrient delivery, temperatures, hydrology, and mixing regimes of lakes. In addition, many of these studies have noted that climate change is not occurring in a static landscape, but rather impacts of climate change and human disturbance are likely to interactively affect freshwater ecosystems (Moore *et al.*, 1997; Meyer *et al.*, 1999; Fox *et al.*, 2001; Stone *et al.*, 2001). Due to these interactions, some basins may be more sensitive to climate change than others. This sensitivity is partly a result of the magnitude and type of human disturbance that is occurring within the basin. For instance, regulated rivers in areas where future climate scenarios predict earlier snowmelt and more winter rain may not experience a shift in the timing of high flows similar to naturally flowing rivers in the area. However, in areas where future climate scenarios predict drier conditions for parts of the year, rivers that are used for water supply could experience even lower discharges, and thus potentially be more sensitive to climate change than rivers in the area that are not as heavily utilized for human water consumption.

Although large-scale warming and cooling trends of the Earth occur naturally, current human-mediated climate changes have reached or exceeded the level of these natural fluctuations (Levine, 1992; Vitousek, 1992; Schindler *et al.,* 1996). The fluctuations in the dynamics of the atmosphere and oceans are potentially of a magnitude to constitute global change. However, it is uncertain what these global changes will mean to the Earth's climate, especially at small spatial scales. The most commonly used tools to predict future climate conditions are global circulation models (GCMs). By definition, these models are coarsely scaled, and their ability to predict localized changes in climate is questionable. Recently there have been efforts to examine the potential impacts of climate change on watershed hydrology by statistically downscaling these GCM models. Downscaling includes using correlations between synoptic-scale climatic variables and local climate to simulate weather at a local scale (Giorgi *et al.*, 1994; Wilby and Wigley, 1997; Wilby *et al.*, 1999; Hay *et al.*, 2000). Another approach uses smaller-scale models to make catchment-level predictions of the potential impacts of climate change on freshwater systems (Leavesley, 1994; Poff *et al.*, 1996; Band *et al.*, 1996; Clair and Ehrman, 1996; Wilby and Wigley, 1997; Wilby *et al.*, 1999).

The objective of this study was to examine the potential impacts of future climate scenarios on river ecosystems at the catchment scale. We utilize available atmospheric–hydrologic models to examine potential changes in flow regime and then discuss the implications of these changes for the riverine ecosystem. We view this analysis as a starting point to understanding the ecological implications of future climate scenarios for riverine ecosystems at the catchment scale. We selected rivers with available scaled-down GCM data that adequately predicted observed data and that allowed us to analyse the effects of future climate scenarios on: (1) two different hydrographs (snow + rain, and rainfall); (2) a system with high future water demands; and (3) a floodplain river with available data on the flows needed to connect the floodplain and the channel. The two case study systems in which we examined the changes in flow regime under future climate scenarios are the Cle Elum River, Washington, and the Chattahoochee-Apalachicola River Basin in Georgia and Florida. In addition, for the Chattahoochee-Apalachicola Basin we placed the potential changes in flow regime that result from future climatic scenarios in perspective by comparing the changes in the flow regime caused by direct human appropriation (e.g. dam construction) to those predicted by future climatic scenarios. These two case studies should help illustrate the implications of future climate scenarios for river ecosystems in the Pacific Northwest and in the southeastern United States, and explore the range of potential changes in flow regime. Our study was limited by data availability, and different GCMs and different statistical downscaling techniques will be used for the two case studies. These differences enhance the range of possibilities that could occur under future climate scenarios.

METHODS

We evaluated current and predicted future flow regimes using Richter *et al.*'s (1996) Indicators of Hydrologic Alteration (IHA). IHA was designed to examine changes in flow regimes caused by dams, but its ability to compare flow regimes makes it an ideal tool for this study. This program takes daily streamflow values and characterizes flow regime in terms of five ecologically significant factors: magnitude, duration, frequency, timing, and rate of change. By dividing the streamflow record into a pre- and post-impact period, the program calculates the percentage change in several ecologically relevant statistics, including magnitude of monthly water conditions, magnitude and duration of annual extreme water conditions, timing of annual extreme water conditions, and frequency and duration of high and low pulses.

The IHA was designed primarily to test for differences in flow regime in distinct pre- and post-impact periods (e.g. as caused by dams). Since we were assessing the more subtle impact of climate on flow regime, we decided to focus on a specific subset of the 32 statistics calculated by the program that were more likely to be sensitive to climate change. Specifically, we focused on mean monthly discharge for each month, magnitude of the 1-, 3-, 7-, 30- and 90-day maximum and minimum flows, and timing of the 1-day maximum and minimum flows. Future climate scenario data for the Chattahoochee-Apalachicola basin were calculated on a weekly time scale, thus we could only calculate the 7-, 30- and 90-day maximum and minimum flows, and we were not capable of calculating the timing of the 1-day maximum or minimum flows (see below). There are several other parameters calculated by IHA including rise rate, fall rate, number of reversals, number of low and high flow pulses, and duration of low and high flow pulses. However, these parameters were either unlikely to be affected by climate change (rise rate, fall rate, and number of reversals) or would not be well predicted by statistically downscaled GCM models (number of low and high flow pulses, duration of low and high flow pulses). Therefore, they were excluded from the analysis. We assessed the inter-annual variability of monthly flows by calculating the coefficient of variation for each month over the period of record or the period modelled.

After quantifying potential changes in flow regime as a result of climate change, we examined implications of these changes on stream functioning and the organisms living within and adjacent to the stream. Specifically, we evaluated potential implications for resident fish species, macroinvertebrates, and riparian plant species.

CASE STUDY 1: CLE ELUM RIVER

The Cle Elum River has a drainage area of 525 km^2 at the gauging station near Rosyln, WA (USGS site 12479000). The one large mainstem reservoir, Cle Elum Lake, in the drainage is managed to supplement flows from March to August for irrigation (Beckman *et al.*, 2000). However, the flows we are examining have been naturalized to remove the effects of the dam (L.E. Hay, personal communication). By looking at the flow regime without the influence of dams, the analysis gives a better illustration of the potential implications throughout the Pacific Northwest rather than just a particular river. Precipitation at Cle Elum, WA, slightly downstream of the Cle Elum River and Yakima River confluence, averages 56.6 cm per year. The river drains the Wenatchee Mountains, which are heavily forested in spruce (*Picea engelmannii*) and Douglas fir (*Pseudotsuga menziesii*) (Carter *et al.*, 1996). This perennial river has a moderately seasonal runoff pattern characterized by a late spring (April–June) high flow period driven by snowmelt and a summer low flow period. The snowmelt signature, along with moderate values for flow predictability, flood predictability, and length of flood-free season, suggests a Rain + Snow type stream (Poff and Ward, 1989; Poff, 1996). Rain + Snow streams are typically western montane streams that are influenced by both annual snowfall and winter rainfall patterns (Poff and Ward, 1989). Therefore, they are likely to have the characteristic snowmelt peak in spring, but warmer winters with heavy precipitation can lead to rain-on-snow events that cause peak flows.

In order to assess the impact of climate change on flow regime, we conducted IHA analysis on three sets of daily stream flow values. First, we calculated IHA hydrologic parameters for observed daily stream flow from 1980 to 1995. Second, we calculated hydrologic conditions for the flow predicted by statistically downscaled GCMs for current climate 1980–1995. This analysis was used to test the sensitivity of statistically downscaled GCMs in predicting known daily streamflow records. Third, we calculated hydrologic parameters for the future flows predicted by statistically downscaled GCMs for 2080–2095. We ran 20 simulations for each of the two statistically downscaled data sets (validation: 1980–1995, and future: 2080–2095). Coefficient of variation for observed data (1980–1995) was calculated for each month. For the two data sets resulting from model predictions, we first calculated an inter-annual coefficient of variation for each month for each simulation and then calculated the mean and standard error of the coefficient of variation from the 20 simulations.

For future climate scenarios, we used the UK Meteorological Office, Hadley Centre's coupled ocean/atmosphere model (HadCM2) forced by changes in combined CO_2 and a sulphate aerosol proxy (Johns *et al.* 1997; Mitchell and Johns, 1997; Wilby *et al.*, 1999). In this model, CO_2 levels increase by 1% a year from 1990 to 2100 (Mitchell and Johns, 1997). For current climate modelling, we ran the same climate model but with observed values of the parameters, such as CO_2 (Wilby *et al.*, 1999). For both climate models, statistical downscaling and hydrologic modelling were performed as described by Wilby *et al.* (1999) and Hay *et al.* (2000). Briefly, with this approach

daily temperature and precipitation from the downscaled GCM output were spatially distributed over the basin using monthly lapse rates calculated from observed data (Wilby *et al.*, 1999). These spatially distributed temperature and precipitation data were then put into the PRMS (Precipitation–Runoff Modeling System) catchment model, which modelled daily stream flows (Leavesly *et al.*, 1983; Leavesly and Stannard, 1995; Wilby *et al.*, 1999; Hay *et al.*, 2000).

Due to inherent variability associated with models, we ran 20 simulations of the downscaling model for both current and predicted future climate scenarios. Each simulation was independent, and we analysed the flow regime resulting from each simulation separately using IHA. For each of the two statistically downscaled model types based on current or predicted future climate, we calculated the mean and standard deviation of each IHA hydrologic parameter to characterize model variability. To evaluate the impact of climate on flow regime, we compared the parameters calculated from the observed data (1980–1995) to parameters calculated from the GCMs with predicted future climate (2080–2095). To assess the ability of statistically downscaled GCMs to predict daily stream flow, we compared parameters calculated from the observed data (1980–1995) to those calculated from the statistically downscaled GCMs with current climate (1980–1995). The models are not capable of precisely replicating the observed data, so we attempted to determine the extent to which the model accurately represented the observed data. We defined a significant change in a parameter as differing from observed data by greater than 2 standard errors.

To differentiate between changes in flow regime resulting from modelling inefficiencies and changes resulting from predicted future climate scenarios, we performed similar comparisons between statistically downscaled GCMs with current climate and statistically downscaled GCMs with future climate scenarios. For instance, if modelled flow regimes based on current climate conditions resulted in values of a parameter that were higher than for the observed flow regime, but the modelled future climate scenario predicted a decrease in the same parameter, we had confidence that the change was a consequence of the future climate scenarios and not an artifact of the statistically downscaled model. However, if the magnitude and direction of changes in a flow regime parameter were similar between modelled current conditions and modelled future climate scenarios, then we concluded that there was not a detectable effect of climate change on that parameter.

The downscaled GCM under current climate conditions (1980–1995) captured the observed seasonal pattern of discharge, but underestimated magnitude of the flow from spring snowmelt (April–June) and overestimated autumn and winter (October–February) low flows (Figure 1). The model significantly overestimated the 1-, 3- and 7-day maxima (Figure 2) and the 1- and 90-day minima (Figure 2). The model was fairly accurate in predicting the timing of the 1-day minimum and maximum. In terms of inter-annual variability, the model slightly overestimated variability from January to May, was much higher than what was observed in September, and underestimated variability in October to December (Figure 3).

The hydrograph under predicted climate for 2080–2095 differed markedly from both the current conditions and the modelled current conditions. In addition, the changes in the hydrograph under predicted future climate were dramatically different from the changes attributable to model inadequacies in predicting current hydrographs. Peak monthly flow shifted from late spring/early summer (April–June) to winter (December–February) indicating a shift from precipitation falling primarily as snow and being stored, to precipitation falling as rain and immediately running off (Figure 1). Spring and summer flows were lower, and the length of summer low flow period was extended in the 2080–2095 hydrograph compared to observed conditions (Figure 1). Timing of the 1-day minimum was about 1 month later under future climate scenarios (28 September) compared to observed conditions (25 August), but the 1-day maximum was almost 6 months earlier under future climate scenarios (4 January) compared to observed conditions (28 May). In addition, the flow regime under predicted future climate scenarios will have an extended period of time with no floods (203 days) compared to observed (82 days) or modeled (81 days) current conditions.

There were no significant changes in the magnitude of the 1-, 3-, 7-, 30- or 90-day maxima under predicted future climate compared to modelled current conditions (Figure 2). This suggests that, on average, the magnitude and duration of yearly floods did not differ between current conditions and those predicted under future climatic scenarios. However, the magnitude of the 1-, 3-, 7-, 30- and 90-day minima were all much lower under predicted future climatic scenarios than under current conditions (Figure 2). This suggests that, on average, the lowest water flows will be lower and low water periods will last longer under predicted future climatic scenarios. This
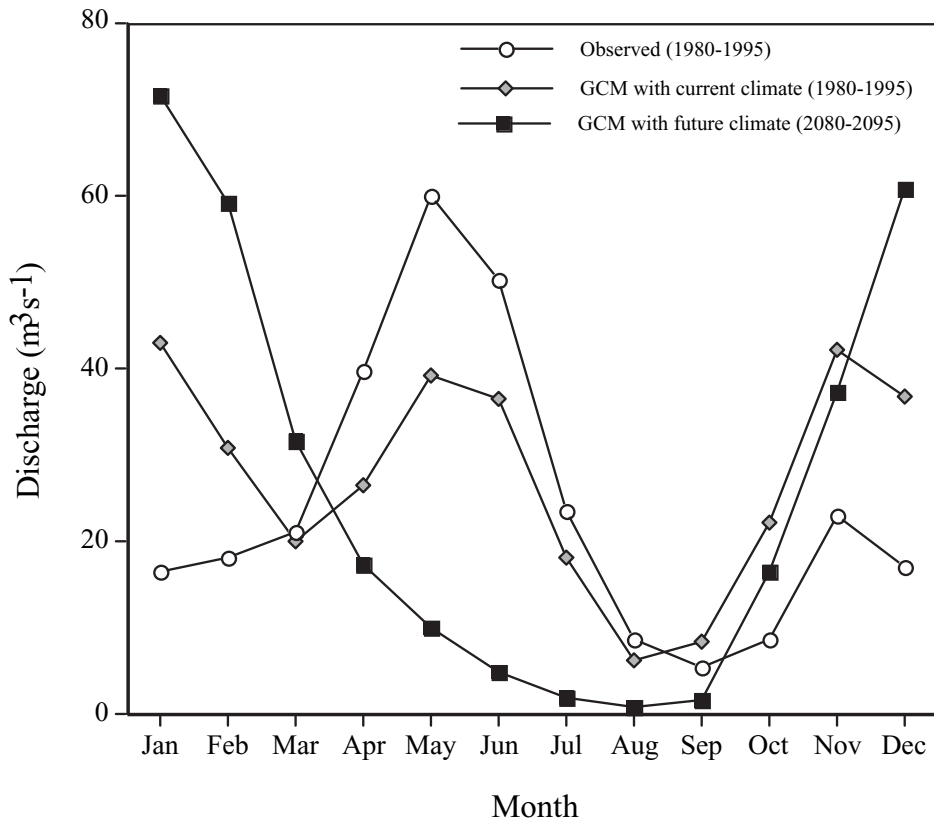
Figure 1. Mean monthly flow of the Cle Elum River, Washington, using observed and downscaled GCM-generated stream flow. Error bars are mean ±1 standard error for the 20 GCM simulations. When not shown, error bars are smaller than the symbol

is consistent with the monthly flow data, which predicted an extended summer low flow period and lower summer flows under simulated future climate scenarios (Figure 1).

We assessed variability by calculating the coefficient of variation of mean monthly discharge over the 15-year timespan. Thus, the coefficient of variation is a measure of inter-annual variation. For the most part, the predicted future coefficient of variation was similar or less than the current coefficient of variation (Figure 3). The exception was in September where the coefficient of variation was much higher under future climatic scenarios. However, it is likely that this large coefficient of variation is a consequence of the model since the coefficient of variation was also much higher in September in the model derived from current climate conditions. Downscaled GCMs are much better at predicting precipitation when large weather systems are dominant than when smaller convective systems are responsible for the majority of precipitation events, such as in the late summer (Wilby *et al.*, 1999). This model artifact may have artificially inflated the coefficient of variation in both model outputs (Figure 3). In addition, the lowest mean flows occur in September, so if there is high variability due to the limited capabilities of the model to predict the small storms that dominate late summer precipitation, this would also lead to an inflation of the coefficient of variation.

Flow regime is directly related to several factors that affect biological communities and ecological processes in river systems (see Poff *et al.*, 1997). For example, lower summer flows can lead to increases in water temperatures and reduced dissolved oxygen. Lower flows also indicate a reduced wetted perimeter, which would decrease habitat availability and impact lateral exchanges between the riparian zone and the stream. A shift in the timing of peak flow can alter the retention time of organic matter (Mulholland *et al.*, 1997), disrupt the recruitment of riparian species that rely on appropriately timed high flows to disperse seeds on to the floodplain (Auble *et al.*, 1994; Rood *et al.*, 1995), and impact the survival of certain fish species whose larval emergence is timed to avoid high spring flows (Seegrist and Gard, 1972; Erman *et al.*, 1988; Hauer *et al.*, 1997).
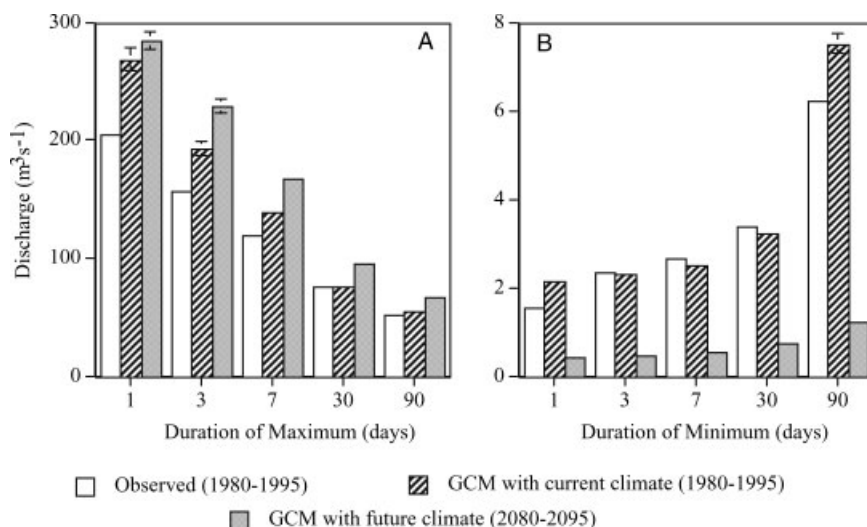
Figure 2. One-, 3-, 7-, 30- and 90-day maxima (A) and minima (B) flows for the Cle Elum River, Washington, using observed and downscaled GCM-predicted stream flows. Error bars are mean ±1 standard error. When not shown, error bars are smaller than the symbol
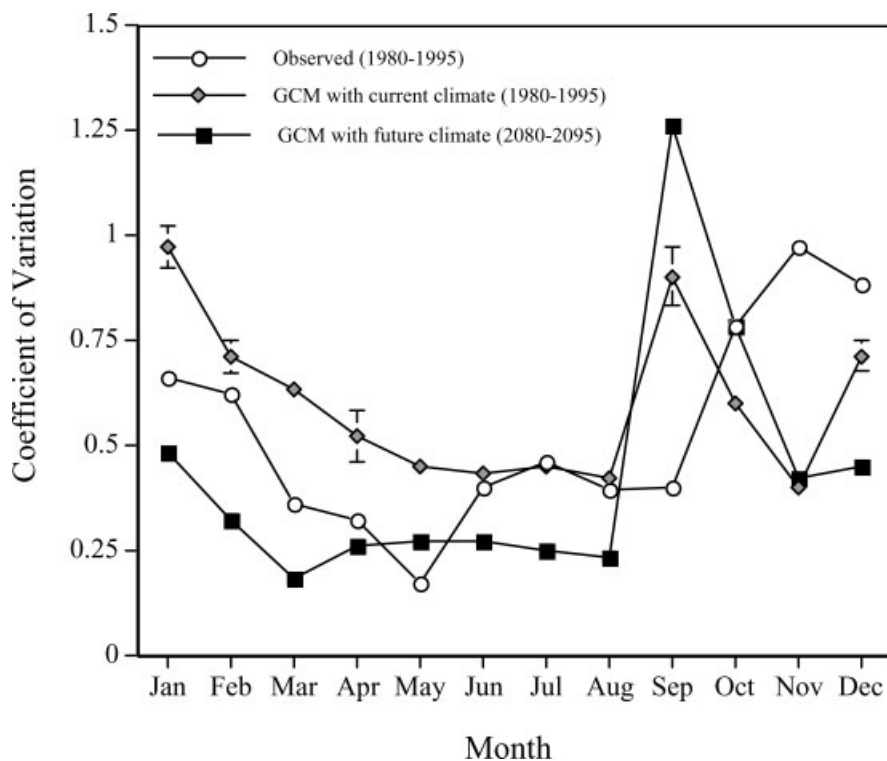

Figure 3. Coefficient of variation for mean monthly flow of the Cle Elum River, Washington, using observed and downscaled GCM-generated stream flow. Error bars are mean ±1 standard error for the GCM data. When not shown, error bars are smaller than the symbol

Although we do not have biological data specific to the Cle Elum River, Cuffney *et al.* (1997) sampled several river systems surrounding the Cle Elum that are also located in the Cascades Ecoregion and are tributaries of the Yakima River. For fishes, Cuffney *et al.* (1997) found that high elevation, cold-water streams with little agricultural influence, such as the Cle Elum, were typically populated by salmonids and sculpins (*Cottus* spp.). The salmonids

included dolly varden (*Salvelinus malma*), brook trout (*S. fontalis*), cutthroat trout (*Oncorhynchus clarki*), coho salmon (*O. kisutch*), spring chinook salmon (*O. tshawytscha*) and rainbow trout (*O. mykiss*). All of these fishes are cold-water species that typically inhabit areas where summer water temperatures usually do not exceed 20–24°C (Eaton *et al.*, 1995). Therefore, increases in summer water temperatures above this threshold could depress or extirpate populations of these fishes. Most of these fish species are either autumn or spring spawners. Therefore, the direction and extent of a shift in peak flow timing will affect different species in different ways. Autumn spawners spawn in the autumn, and the fry emerge from the gravel before the spring snowmelt. Spring spawners spawn after the spring snowmelt, and the fry emerge during the summer or early autumn. The future scenarios that we evaluated predicted a dramatic shift in peak flow from May to January (Figure 1). This degree of shift would likely adversely affect the autumn spawners (dolly varden, brook trout, and coho salmon) whose eggs could be scoured and whose fry would potentially be washed away and/or covered with sediment (Montgomery *et al.*, 1999). Spring spawners (spring chinook and rainbow and cutthroat trout) are less likely to be adversely affected by this predicted shift in peak flow, although they would probably be affected by reduced habitat availability resulting from extended summer low flow conditions (see Figure 1). Sixty per cent of the chinook salmon in the Yakima Basin spawn in the Cle Elum, so shifts in the hydrograph that might affect these species could result in dramatic population declines basin-wide (Beckman *et al.*, 2000).

One likely consequence of the shift from snowmelt to winter rain flow regime is that flood frequency will increase because precipitation from individual winter storms will not be stored as snow with only one runoff event during snowmelt. These earlier floods would reduce the retention time of organic matter, thereby reducing food availability for detritivorous macroinvertebrates. Cuffney *et al.* (1997) found that these high elevation streams were inhabited by insects (predominantly mayflies, stoneflies, and caddisflies) that utilized allochthonous organic matter (relatively high shredder richness) rather than autochthonous organic matter (relatively low scraper richness). Moreover, a longer low flow period in the summer could benefit algae because of the reduction in shear stress (Biggs, 2000) and the increased water temperatures. Therefore, the importance of algae in the benthic food web could become more significant. This could cause a switch in the macroinvertebrate community from shredder-dominated to scraper-dominated. In addition a shift in high flow timing from late spring to winter would have significant negative impacts on the abundance of many aquatic insects, especially those that grow in the winter and emerge prior to the predictable high spring flows. Work in California streams that have a Mediterranean climate (winter floods and low summer flows) have documented important changes in invertebrate community composition and food web structure when winter floods are stored by dams and released as high summer flows (Power *et al.*, 1996, Wootton *et al.*, 1996). This example provides a basis for asserting that seasonal shifts can have significant impacts on benthos.

CASE STUDY 2: APALACHICOLA–CHATTAHOOCHEE–FLINT RIVER BASIN

The Chattahoochee–Apalachicola River Basin has its headwaters in Georgia and Alabama and extends approximately 620 km before emptying into Florida's Apalachicola Bay in the Gulf of Mexico. The basin has a drainage area of 50 764 km². Fifty-eight per cent of the basin is forest, 29% of the basin is agriculture, and 5% of the basin is urban and suburban land uses (Frick *et al.*, 1998). Average precipitation ranges from 114 to 152 cm per year. There are 14 reservoirs on the mainstems of the two rivers. These dams and reservoirs are used for hydropower, recreation, water supply and flood control. The first large dams built, J. Woodruff and Buford dams, were completed in 1957. The Chattahoochee River runs through the city of Atlanta and has been impacted by urbanization including water withdrawals, wastewater plant effluents, and sedimentation. The Apalachicola River is formed by the confluence of the Chattahoochee and Flint Rivers and is a wide meandering Coastal Plain river with extensive floodplains. The channel has been dredged since 1954 to allow for barge traffic and the resulting channel degradation has reduced the connectivity between the river and its floodplain (Light *et al.*, 1998).

We used one site from the Chattahoochee and one from the Apalachicola to assess the impact of dams, surface water demand schemes, and climate scenarios on flow regime. The Chattahoochee River site at Whitesburg, Georgia, is downstream of Atlanta and one major reservoir (Lake Lanier formed by Buford Dam). The Apalachicola River site at Chattahoochee, Florida, is downstream of Lake Seminole Reservoir and all the dams on the Chattahoochee and Flint Rivers. We chose these sites because of their location on the river and the length of

the gauging station records available. In addition, Light *et al.* (1998) have extensive data on flows needed to connect the floodplain and the channel for the Apalachicola River at Chattahoochee, Florida.

For future climate scenarios, we used the Canadian Center for Climate Modeling and Analysis CGCM1 model for the years 2018–2048. This model predicts a warmer and drier climate for the southeast. These scenarios are derived from coupled atmospheric–ocean global climate model experiments with transient greenhouse gas and sulphate aerosol forcing. This is a transient model, which means that the climate is changing gradually over time. The original data set for this model has a resolution of 3.5×3.5 degrees, but the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) transferred this to 0.5×0.5 degrees for the United States. To calculate stream flow, we applied a procedure using regression analysis between runoff and climatological parameters (Georgakakos and Yao, 2000). Therefore, to calculate future weekly stream flow, we used the climate parameters from the CGCM1 model downscaled by VEMAP with the regression model to predict weekly runoff and stream flow (Georgakakos and Yao, 2000). These weekly stream flow values were translated into daily stream flow values by assuming a linear relationship in flow from one week to the next.

The demand projections used in this model were created by the Alabama Office of Water Resources, the Environmental Protection Division of the Georgia Department of Natural Resources, the Northwest Florida Water Management District, and the Mobile District Corps of Engineers for the Apalachicola–Chattahoochee–Flint Comprehensive Study (USACE, 1998). They developed three levels of demand (low, moderate and high), which varied depending on conservation measures and agricultural demand. We used the moderate demand level. In this scenario, water use projection for municipal users was based on 1990–1993 residential use patterns and projection for industrial use was based on 1990 non-residential water use patterns. In both cases, the moderate demand level assumed passive conservation measures. Projected changes in population, employment and housing characteristics drove water demand projections in the basin. The agricultural water demand assumed a continuation of the current rate of economic and technological growth and no substantial change in national agricultural policy, price support, or agricultural export. The water demand projections for agriculture also assumed continued irrigation with no conservation mechanisms. The demand projections do not take into account ground-water pumping, which is significant in the Coastal Plain. Therefore, the agricultural demand is underestimated and our analysis is limited to the effects of surface-water demands and withdrawals.

In order to assess the impact of dams, future water demand scenarios, and future climate scenarios on the flow regime of the Chattahoochee–Apalachicola River Basin, we evaluated flow regimes under three different conditions using IHA. First, we calculated IHA parameters for observed daily flows prior to construction of the major large reservoir-producing dams on the mainstem of the Chattahoochee (Buford, West Point, Walter F. George, and J. Woodruff) and compared them to IHA parameters calculated from current observed daily stream flows (1965–1995). There are several smaller dams on the Chattahoochee that were built earlier than the large dams listed above. However, there is not sufficient flow data for the time period prior to the construction of these small dams to conduct an IHA analysis. Therefore, our 'pre-dam' data set is actually pre-large-reservoir dams. For the Chattahoochee River at Whitesburg, we used available pre-dam flow records from 1938–1950 and for the Apalachicola River at Chattahoochee available pre-dam flows were from 1928–1950. Second, to evaluate the impact of water demand in the year 2050, we subtracted 2050 demand from current observed stream flow conditions (1965–1995), calculated the IHA parameters for current conditions with 2050 demand superimposed, and compared the parameters to current conditions. Third, to assess the combined impact of future climate scenarios and water demand, we calculated IHA parameters for daily flows interpolated from weekly flows predicted by the model based on the climate scenario parameters–stream flow relationship described above with 2050 demand subtracted.

Unlike the Cle Elum River, the statistical downscaling procedure for the Chattahoochee–Apalachicola basin was only simulated once. Therefore, the variability and standard errors for these data sets represent inter-annual variability rather than inter-simulation variability. When a parameter calculated from the flow regime of the future climate scenario is greater than the value calculated from the observed data, the value of the parameter under future climate scenario is out of the range of variability typically occurring within the time frame of the observed data. For instance, if mean 7-day maximum flow under current conditions is less than the mean minus standard error of the 7-day maximum flow under pre-dam conditions, then the current maximum flow is lower than that typically experienced in the pre-dam time period.
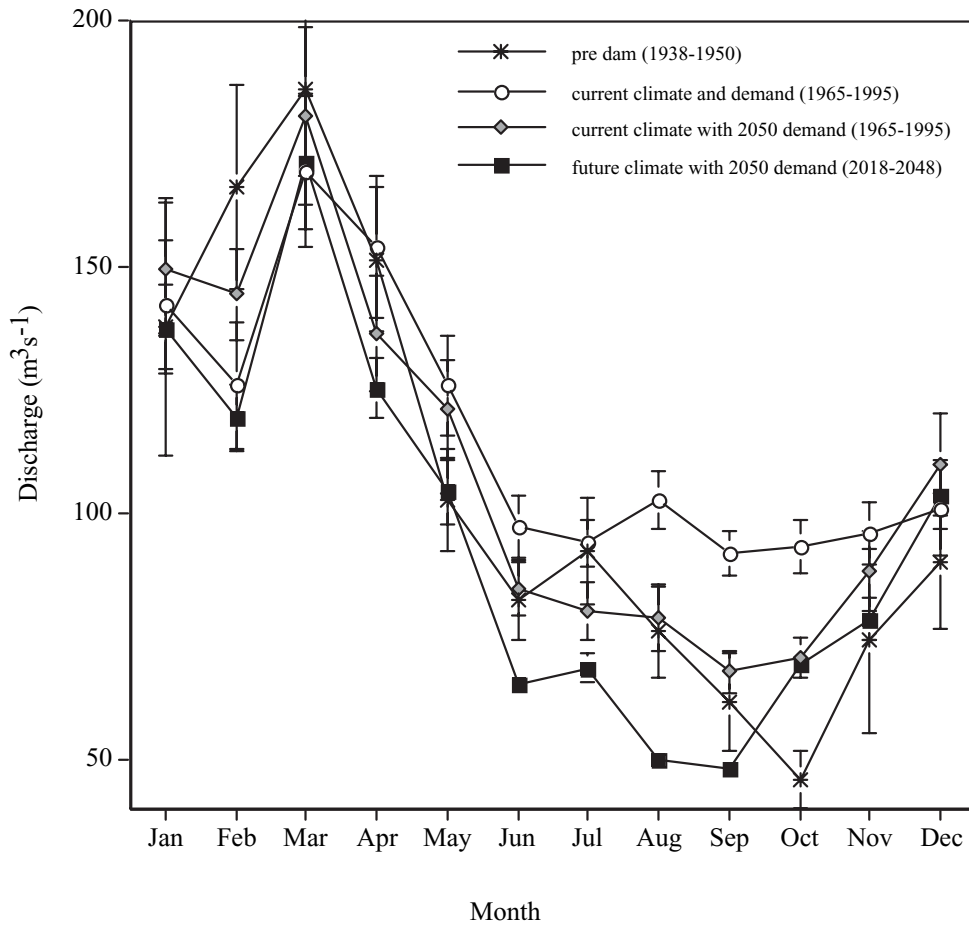
Figure 4. Mean monthly flow of the Chattahoochee River at Whitesburg, Georgia, under different management and climate scenarios: pre-dam conditions; current climate and management (1965–1995); current climate (1965–1995) and 2050 management; predicted future climate (2018–2048) and 2050 water demand. Error bars are mean ± 1 standard error. When not shown, error bars are smaller than the symbol

Chattahoochee River at Whitesburg

Although only 12 years of pre-dam records are available at this site, flows before the construction of dams were typified by high winter and spring flows and lower summer and especially autumn flows (Figure 4). The construction of Buford dam on the Chattahoochee River upstream of Whitesburg resulted in an approximately $28 \, m^3 \, s^{-1}$ increase in summer flows (Figure 4). However, expected increases in demand for water in 2050 would decrease summer and autumn flows (June–October) even without any climate change (Figure 4). Management changes and expected demand increases would lead to decreased mean monthly flow in the summer and autumn by almost $28 \, m^3 \, s^{-1}$. Under predicted future climate scenarios and 2050 demand, summer flows would decrease even further (Figure 4). Mean monthly flow for summer months (June–September) were predicted to decrease another 14–$28 \, m^3 \, s^{-1}$. Under current climate and demand, mean flow in the Chattahoochee River at Whitesburg, Georgia, for the summer months of June to September is $99 \, m^3 \, s^{-1}$. Under 2050 demand and future climate scenarios, average flow for these months was predicted to be $57 \, m^3 \, s^{-1}$.

The average 7-, 30- and 90-day maximum flows were similar among the three water conditions (pre-dam construction, current conditions, and current climatic conditions but increased demand) (Figure 5). However, under future climate scenarios and expected demand, the 7-, 30- and 90-day maxima were all lower than current conditions and current conditions with 2050 demand (Figure 5). The average 7-, 30- and 90-day minima increased after construction of the dams (Figure 5). Demand increases expected in the future lowered the 30- and 90-day minima,
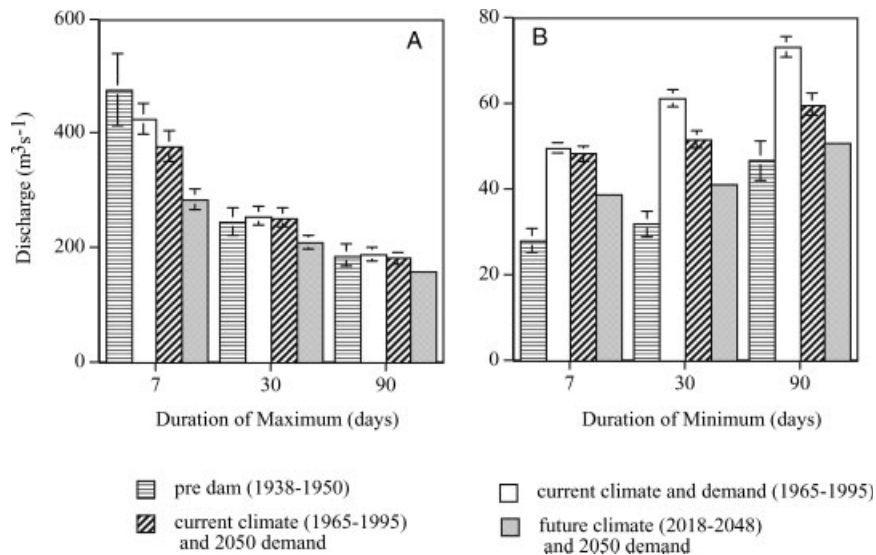

Figure 5. Seven-, 30- and 90-day maxima (A) and minima (B) flows of the Chattahoochee River at Whitesburg, Georgia, under four different climate and management scenarios: pre-dam conditions (1938–1950); current climate and management (1965–1995); current climate (1965–1995) and 2050 management; predicted future climate (2018–2048) and 2050 management. Error bars are mean ±1 standard error

but had little impact on the 7-day minimum (Figure 5). Future climate scenarios combined with expected demand increases were predicted to lower the minimum flow at all three time scales, 7-, 30- and 90-days (Figure 5). However, these low flows are still higher than those experienced from 1938 to 1950.

Construction of Buford Dam decreased the variability of flow in the river during summer and winter and slightly increased flow variability in the spring (Figure 6). Increases in demand under current climate conditions would slightly increase the variability of the system in the summer. Future climate scenarios coupled with future demand would decrease variability of river flow throughout the year (Figure 6). The predicted decreased system variability under future climate scenarios and future demand appears to primarily be the result of the climate scenario since the increased demand under current conditions actually slightly increased system variability (Figure 6).

Apalachicola River at Chattahoochee, Florida

Dam construction did not significantly alter mean monthly flow in the Apalachicola (Figure 7), although winter flows (January and February) were slightly higher under current conditions. Increased water demand would slightly lower mean monthly flow from late spring to late summer (April to September) (Figure 7). Future climate scenarios coupled with increased demand produced even lower flows from late winter through to autumn (February to October) (Figure 7).

Seven-, 30- and 90-day maxima for current conditions were similar to those experienced prior to large impoundments (Figure 8). Moreover, 2050 demand levels did not appear to alter these maxima (Figure 8). Future climate scenarios combined with 2050 demand levels would decrease the 7-, 30- and 90-day maxima (Figure 8). Seven-, 30- and 90-day minimum flows for current conditions were also similar to those experienced before large impoundments (Figure 8). However, when future water demands were imposed on current conditions, the 7- and 30-day minima decreased (Figure 8). When future climate scenarios and future water demands were used, the 7-, 30- and 90-day minima were all lower than current conditions and current conditions with future demand (Figure 8).

In general, variability within the system declined after dam construction. Increased demand did not appear to significantly alter the variability of the system. However, under future climate scenarios, the variability in the system was predicted to be lower than under current conditions (Figure 9). The lowering of the variability appears to
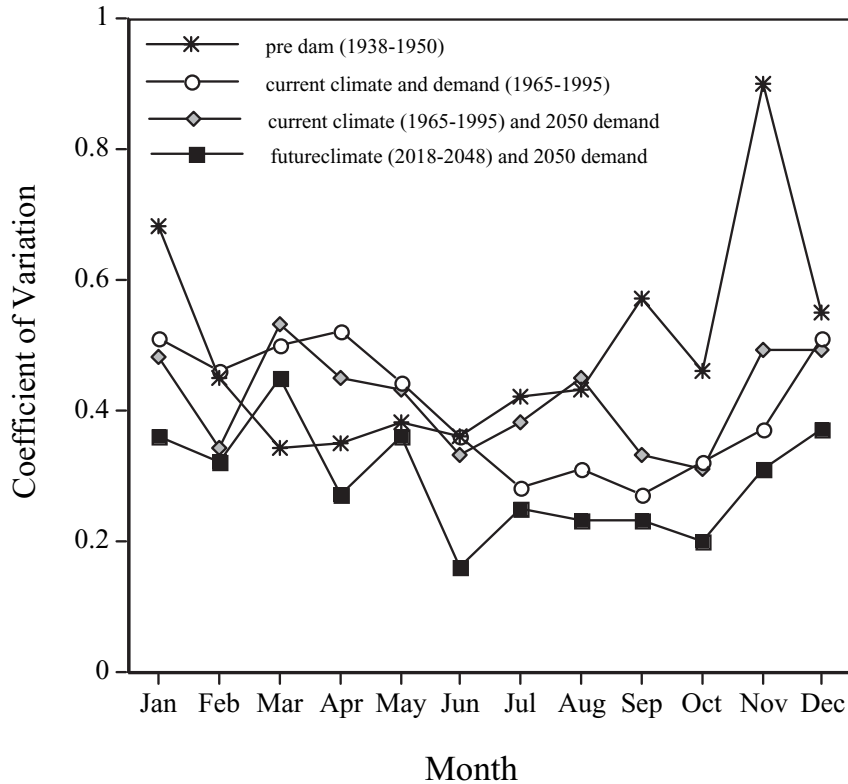
Figure 6. Coefficient of variation for mean monthly flow of the Chattahoochee River at Whitesburg, Georgia, under four different climate and management scenarios: pre-dam conditions (1938–1950); current climate and management (1965–1995); current climate (1965–1995) and future management (2050); and predicted future climate (2018–2048) and management (2050)

be driven by the future climate scenario rather than the increased demand, since the increased demand did not have a noticeable impact on system variability (Figure 9).

Seventy-three of the 91 species of fishes known to inhabit the Apalachicola River have been collected in river floodplains under a variety of hydrologic conditions (Light *et al.*, 1998). Fishes in the Apalachicola River system primarily spawn from April to July, and therefore the extent of connected aquatic habitats during this time period represents the potential availability of spawning habitat (Light *et al.*, 1998; Freeman, 1998). Under increased demand and future climate scenarios, the percentage of the floodplain connected to the river will decrease. For instance the predicted 90-day maximum flow under 2050 demand and climate is $935 \, m^3 \, s^{-1}$, at which point about 50% of the floodplain is connected (Light *et al.*, 1998). Under current conditions the 90-day maximum flow is $1167 \, m^3 \, s^{-1}$ at which point about 68% of the floodplain is connected to the river (Light *et al.*, 1998). Thus, in an average year 18% of the floodplain typically available for fish to forage and spawn during the critical spawning period under current conditions would be unavailable under 2050 demand and climate.

Currently, the movement of fish between the main channel and the tributaries requires a flow of $312 \, m^3 \, s^{-1}$ at the Chattahoochee gauge (Light *et al.*, 1998). Prior to 1954, there were no days from May to November below this flow level with restricted tributary access; however, after 1981 there was a median of 66 days below this flow threshold. Under 2050 demand and future climate scenarios, mean monthly flow for August, September, and October and the average 90-day minimum are all below the $312 \, m^3 \, s^{-1}$ threshold, which means the fish could not move between the main channel and the tributaries.

Hence, the presence of specific habitat types is often dependent on the presence of certain flow levels. For instance, in the Apalachicola River near the Chattahoochee gauge, the area of raceway and shallow pool habitat increases by more than 25% as flow increases from 240 to $325 \, m^3 \, s^{-1}$ (Freeman *et al.*, 1997). Under 2050 demand and future climate scenarios, the area of this type of habitat could be drastically reduced as the mean monthly flows
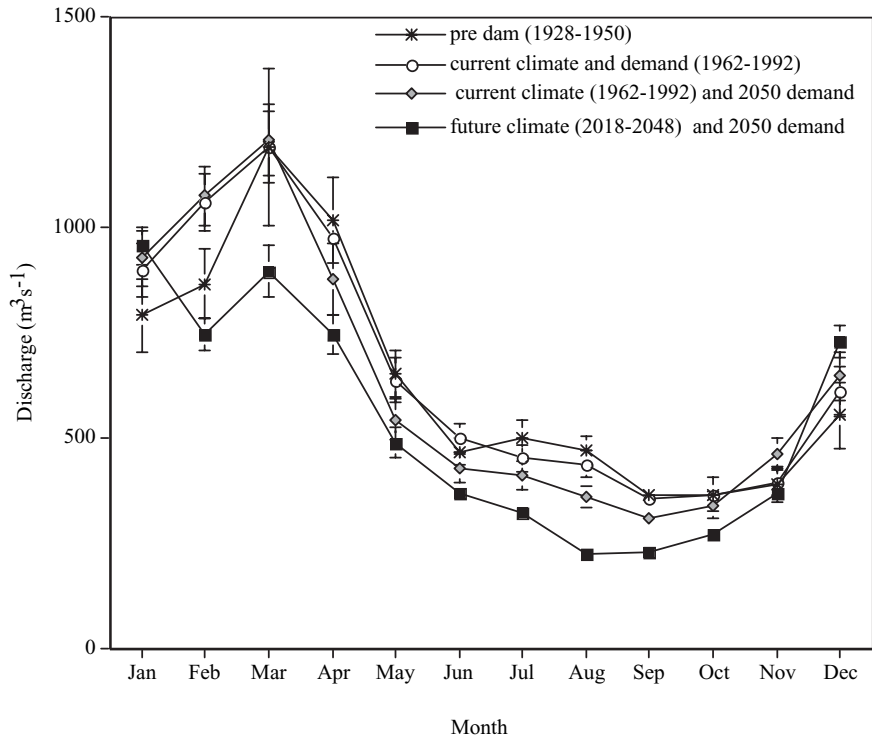
Figure 7. Mean monthly flow of the Apalachicola River at Chattahoochee, Florida, under four different management and climate scenarios: pre-dam conditions (1928–1950); current climate and management (1962–1992); current climate (1962–1992) and 2050 management; and predicted future climate (2018–2048) and 2050 water demand. Error bars are mean ±1 standard error
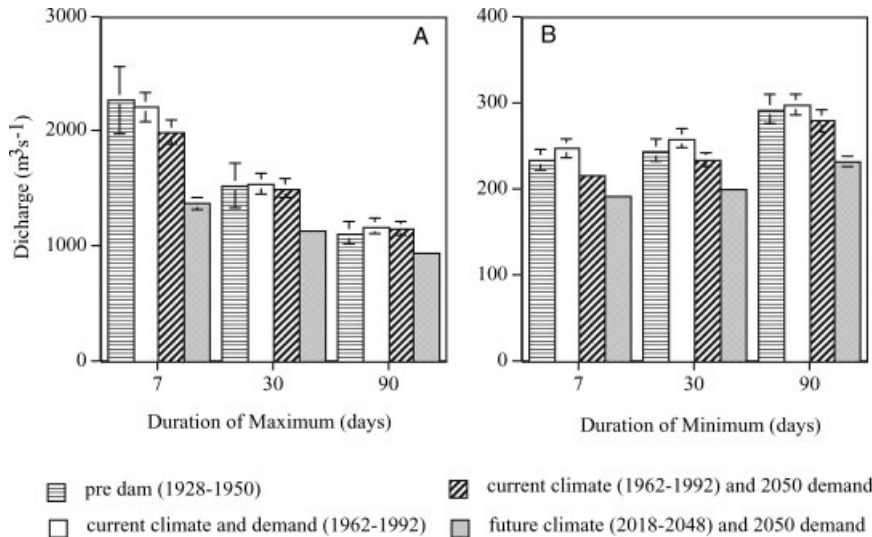

Figure 8. Seven-, 30- and 90-day maxima (A) and minima (B) flows of the Apalachicola River at Chattahoochee, Florida, under four different climate and management scenarios: pre-dam conditions (1928–1950); current climate and management (1962–1992); current climate (1962–1992) and 2050 management; predicted future climate (2018–2048) and 2050 management. Error bars are mean ±1 standard error
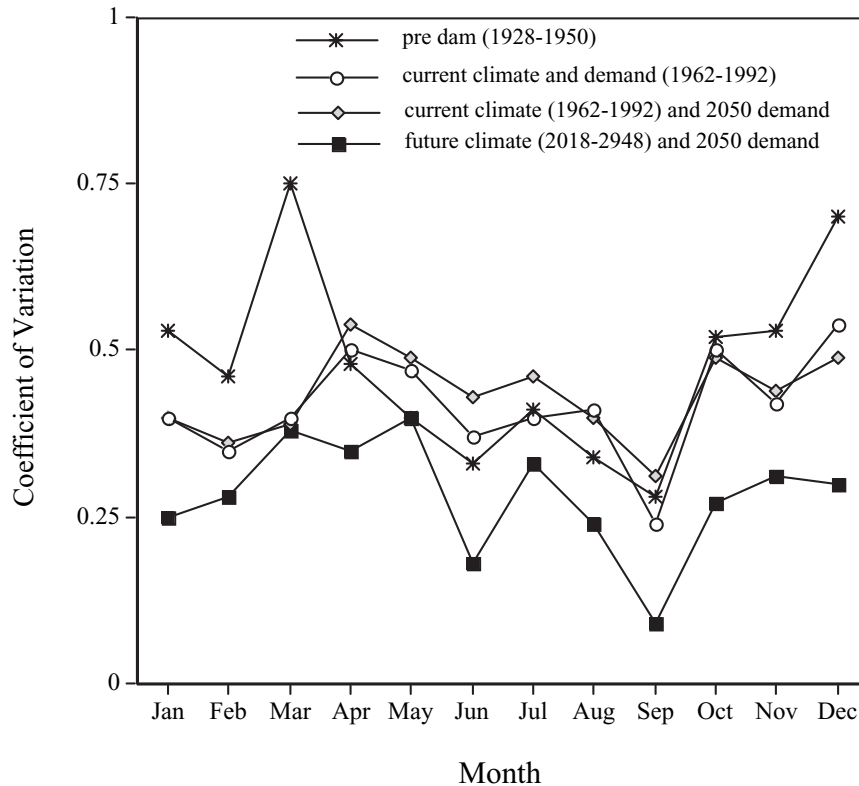
Figure 9. Coefficient of variation for mean monthly flow of the Apalachicola River at Chattahoochee, Florida, under four different climate and management scenarios: pre-dam conditions (1928–1950); current climate and management (1962–1992); current climate (1962–1992) and future management (2050); and predicted future climate (2018–2048) and management (2050)

for August and September are not predicted to exceed $227\,m^3\,s^{-1}$. Raceway habitat makes up less than 3% of the available habitat at flows below $227\,m^3\,s^{-1}$ and shallow pool makes up around 10–15% of the available habitat (Freeman *et al.*, 1997). These percentages decline as discharge falls below $142\,m^3\,s^{-1}$ (Freeman *et al.*, 1997).

One of the major concerns with the Chattahoochee River at Whitesburg is the ability to assimilate the large amount of wastewater treatment plant effluent it receives daily. Currently, during baseflow conditions 20% of the streamflow at Whitesburg is wastewater treatment plant effluent (USACE, 1998). Under the 2050 demand scenario with current climate conditions the percentage of baseflow that is effluent will increase to 33% (USACE, 1998). With the decreased mean monthly flow predicted by the future climate scenarios (Figure 4), percentage effluent is predicted to increase further. In addition, decreased flow is often associated with increased temperature which, in turns, lowers dissolved oxygen. Thus, a higher effluent percentage could increase biological oxygen demand and combine with higher temperatures to potentially lead to low oxygen levels and problems for aquatic organisms.

These analyses were performed using GCM models (HadCM2, CGCM1) that were used by The National Assessment Synthesis Team, US Global Change Research Program (2001). The more recent models that will be used for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) include more recent editions of both the Hadley Centre's coupled ocean/atmosphere model (HadCM3) (Pope *et al.*, 2000) and the Canadian Center for Climate Modeling Analyses CGCM2 (IPCC, 2004). The more recent Hadley Centre model predicts mean annual temperatures to increase by 1–2°C in the Pacific Northwest of the USA Winter is predicted to be warmer and wetter, and summer is predicted to be warmer and drier than current conditions. Therefore, these more recent models are consistent with both the previous model and our predictions of a shift in peak flows to earlier in the year as a result of more winter rain and an increase in the length of the summer low flow

period for the Cle Elum River. The more recent Canadian Center model predicts mean annual temperatures to increase and mean annual precipitation to decrease in the southeast USA. Therefore, the more recent models are also consistent with the previous model and our predictions of lower maximum and minimum flows for the Apalachicola–Chattahoochee River system.

CONCLUSION

These case studies illustrate some of the types of changes to river ecosystems under future climate scenarios. Changes in timing and form of precipitation can affect the timing of maximum and minimum flows as we saw in the Cle Elum, where future scenarios predicted more winter rains and less winter snows. In addition, human demands for fresh-water can exacerbate the situation in areas that are predicted to have less rain under future climate scenarios. We saw this situation in the Chattahoochee–Apalachicola basin, where future climate scenarios coupled with increased human demand resulted in lower high and low flows. In both cases, the changes in the flow regime indicated changes in habitat availability during times of the year that are critical for the survival of fish and other organisms. Changes in the timing of the peak flows could affect survival of salmon species in the Cle Elum and longer low flows in the summer could lead to increased importance of autochthonous resources. Lower peak flows in the Apalachicola could further disconnect the floodplain from the channel which would dramatically reduce the availability of that habitat for fish spawning and for young-of-the-year fish. In addition, the lower flows could mean reductions in in-channel habitat such as raceways and shallow pools as a result of the wetted width of the channel being reduced. Changes in flow regime as a result of changes in climate will be gradual, unlike the abrupt changes that result from dam construction or increased water withdrawal.

Future climate scenarios can cause dramatic shifts in flow regimes, which influences ecological processes in aquatic ecosystems. Shifts in timing of flood events, changes in seasonal flow regimes, and changes in the magnitude of baseflows can all influence organisms within the streams and ecosystem processes. In addition, human alteration of rivers and flow regimes through channelization, dams and water withdrawals can interact with these climate changes to further alter the functioning of ecosystems. These types of analyses provide possible scenarios of the type and magnitude of hydrologic changes under future climates and implications for freshwater organisms and ecosystem processes.

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