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Response of river metabolism to restoration of flow in the Kissimmee River, Florida, U.S.A.

DAVID J. COLANGELO
Kissimmee Division, South Florida Water Management District, West Palm Beach, FL, U.S.A.

SUMMARY

1. The single station diel oxygen curve method was used to determine the response of system metabolism to backfilling of a flood control canal and restoration of flow through the historic river channel of the Kissimmee River, a sub-tropical, low gradient, blackwater river in central Florida, U.S.A. Gross primary productivity (GPP), community respiration (CR), the ratio of GPP/CR (P/R) and net daily metabolism (NDM) were estimated before and after canal backfilling and restoration of continuous flow through the river channel.
2. Restoration of flow through the river channel significantly increased reaeration rates and mean dissolved oxygen (DO) concentrations from <2 mg L^{-1} before restoration of flow to 4.70 mg L^{-1} after flow was restored.
3. Annual GPP and CR rates were 0.43 g O_2 m^{-2} day^{-1} and 1.61 g O_2 m^{-2} day^{-1} respectively, before restoration of flow. After restoration of flow, annual GPP and CR rates increased to 3.95 O_2 m^{-2} day^{-1} and 9.44 g O_2 m^{-2} day^{-1} respectively.
4. The ratio of P/R (mean of monthly values) increased from 0.29 during the prerestoration period to 0.51 after flow was restored, indicating an increase in autotrophic processes in the restored river channel. NDM values became more negative after flow was restored.
5. After flow was restored, metabolism parameters were generally similar to those reported for other blackwater river systems in the southeast U.S.A. Postrestoration DO concentrations met target values derived from free flowing, minimally impacted reference streams.

Keywords: dissolved oxygen, Kissimmee River, metabolism, primary productivity, river restoration

Introduction

Metabolism estimates are often used to classify aquatic ecosystems because they are determinants of biomass and trophic structure within a system and can provide an integrated response to a broad range of changes and disturbances within a watershed. Metabolism measurements have been used to indicate changes in the condition of rivers and wetlands (McCormick, Chimney & Swift, 1997; Bunn, Davies & Mosisch, 1999; Mulholland, Houser & Maloney, 2005; Uehlinger, 2006). Therefore, metabolism measurements also should be useful in evaluating restoration and recovery of degraded riverine ecosystems.

Gross primary productivity (GPP) and community respiration (CR) estimates in this study are measures of whole system metabolism. GPP represents photosynthetic production of organic matter and CR is the total consumption of organic matter supplied from sources both within (autochthonous) and outside (allochthonous) an ecosystem (Mulholland *et al.*, 2001). Daily changes in dissolved oxygen (DO) within the water column of a river can be used to estimate GPP and CR (Odum, 1956; Odum & Hoskins, 1958; USGS, 1987; Bott, 2006). The ratio of GPP to CR (P/R) is useful in determining whether a system is autotrophic or heterotrophic. If P/R is >1, the system produces more organic matter than it consumes (autotrophic) and if P/R is <1 the system consumes

Correspondence: David J. Colangelo, Kissimmee Division, South Florida Water Management District, 3301 Gun Club Road, West Palm Beach, FL 33406, U.S.A. E-mail: dcolang@sfwmd.gov

more organic matter than it produces (heterotrophic). These ecosystem level measurements are valuable because they are inclusive of the organisms within the system and their abiotic environment.

The Kissimmee River was once a 166-km long, free flowing, low gradient, blackwater river but was channelised and impounded between 1962 and 1971 (Koebel, 1995). Channelisation resulted in elimination of 12 000–14 000 ha of floodplain wetlands and degraded fish and wildlife habitat and water quality (Toth, 1993). Flow through the river channel was eliminated because of dredging of the flood control canal C-38. After channelisation, virtually all flow was directed through canal C-38 rather than through the remnant river channel. Because water levels could now be artificially controlled, variation in water depth decreased and the river was essentially disconnected from the floodplain. Chronically low DO concentrations in the remnant river channel became a problem shortly after channelisation. A grass roots movement to restore the river, which began before the channelisation project was complete, eventually led to the United States Congress authorising the Kissimmee River Restoration project in 1992.

The Kissimmee River restoration project seeks to restore the prechannelisation habitat structure and function of the river channel-floodplain ecosystem (Toth *et al.*, 1995). Restoration of flow to the river channel and re-inundation of the adjacent floodplain are expected to affect biological and physical components that are directly or indirectly related to river metabolism. These components include hydrology, water quality, vegetation, aquatic invertebrates, reptiles and amphibians, fish and birds (Toth *et al.*, 1995).

Dissolved oxygen was chosen as a metric for evaluating the success of the restoration project because it is essential to the metabolism of most aquatic organisms and can impact the productivity of aquatic ecosystems (Wetzel, 2001). Oxygen concentrations can influence growth, distribution and structural organization of aquatic communities as well as the solubility and availability of nutrients. No DO or metabolism data from the historic (prechannelisation) Kissimmee River exist. However, reference conditions for DO concentrations in the river before channelisation were derived using data from seven minimally impacted, free-flowing, blackwater streams in south Florida (Colangelo & Jones, 2005a). Metabolism values from the literature were used as a reference to compare with estimates from the postrestoration Kissimmee River.

The first of four phases of the restoration began in June 1999 and was completed in February 2001. Phase I consisted of backfilling 12 km of canal, grading spoil areas to the original floodplain elevations, recarving and reconnecting sections of river channel that were destroyed during channelisation and reestablishing flow through 24 km of continuous river (Colangelo & Jones, 2005b). The restoration project is a joint partnership between the South Florida Water Management District and United States Army Corps of Engineers.

The objectives of this study were to: (i) estimate metabolism of the Kissimmee River before and after restoration, (ii) compare prerestoration and postrestoration metabolism and DO data to determine if changes have occurred and (iii) determine if postrestoration metabolism estimates and DO concentrations are similar to reference streams.

Methods

Study area

The Kissimmee River is a fourth to fifth order river located between Lake Kissimmee and Lake Okeechobee in central Florida, U.S.A. (Fig. 1). The watershed encompasses 1963 km^2, and the river and floodplain slope to the south from an elevation of approximately 15.5 m at Lake Kissimmee to approximately 4.6 m at Lake Okeechobee (approximately 6–9 cm km^{-1}) (Koebel, 1995). The channelised system consists of a series of impounded reservoirs (Pools A–E) separated by water control structures (S-65 to S-65E). The 2–3 m deep, 15–30 m wide original river channel is intersected by a 9-m deep, 100-m wide flood control canal (C-38), leaving only stagnant, remnant river channel sections on either side. The regional climate is humid, sub-tropical with nearly equal length wet (June to November) and dry (December to May) seasons and an average yearly rainfall of 135 cm.

The study area is located within a 24-km long section of restored river channel between water control structures S-65A and S-65C. Before canal backfilling and restoration of flow, the river channel was largely covered with floating mats of vegetation (dominant species included *Scirpus cubensis* Poepp. & Kunth, *Pistia stratiotes* L., *Salvinia minima* Baker) (Toth

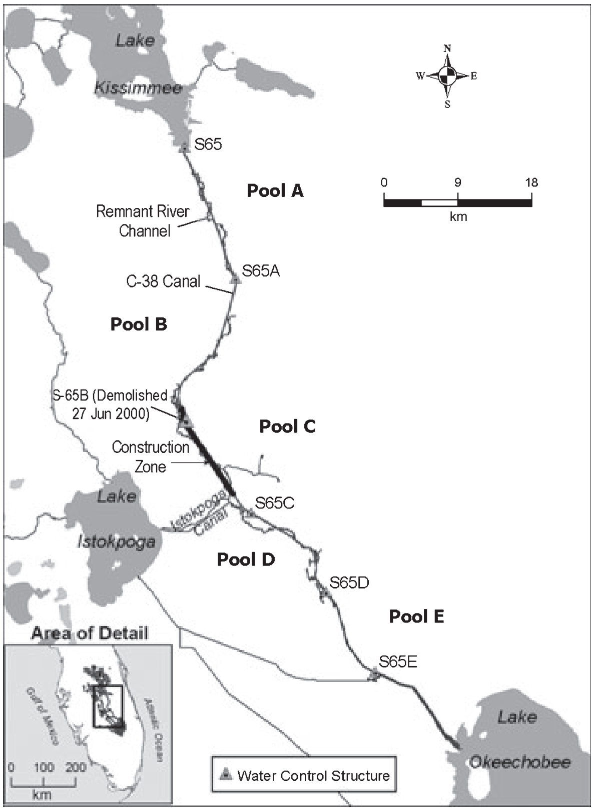

Fig. 1 The channelised Kissimmee River and locations of water control structures in the upper and lower Kissimmee basins. Construction zone represents the area where canal backfilling, river channel recarving and spoil degrading occurred between June 1999 and February 2001.

et al., 1995) and had a thick (average 14 cm) layer of dead and decaying aquatic vegetation, which had accumulated over the original sandy bottom (Anderson & Chamberlain, 2005). Most areas of the river channel received only limited shading from riparian vegetation but were heavily shaded by floating and mat forming aquatic vegetation (Bousquin, 2005). The floodplain of the prerestoration channelised system consisted of mostly unimproved pasture.

The restored section of the river channel has received continuous flow since June 1999 (the river channel began receiving flow at the beginning of phase I construction). As flow was restored, average thickness of organic deposition overlying the river channel bottom decreased to 4 cm (a reduction of 71% from prerestoration conditions) and formation of sand point bars (a characteristic of the river before channelisation) occurred (D. Anderson, personal communication). Restoration of continuous flow also reduced the percentage of the surface of the river channel covered by floating and mat forming vegetation from 57% to 16% (S. Bousquin, personal communication).

Table 1 Physical characteristics of reference streams and the prechannelised Kissimmee River

Stream	Length (km)	Gradient (cm km^{-1})	Temperature (°C)
Arbuckle Creek	39.8	6.2	24.99
Boggy Creek	18.8	2.4	21.41
Fisheating Creek	85.3	2.2	24.98
Josephine Creek	19.3	5.5	24.57
Lake Marion Creek	13.5	2.8	22.07
Catfish Creek, S. Branch	13	–	22.78
Tiger Creek	3.7	3.6	23.61
Prechannelisation Kissimmee River	166	6.0–9.0	–

Temperature data represent mean values. Data are from the South Florida Water Management District dbhydro database.

Reference streams

In the absence of prechannelisation data for the Kissimmee River, reference streams were chosen based on similarities to the Kissimmee River before it was channelised. Data from these reference streams were used to develop success criteria for restoration. Prechannelisation metabolism estimates for the Kissimmee River do not exist. Therefore, metabolism estimates were taken from the literature to compare with the postrestoration Kissimmee River. DO data also were used to measure the success of restoration activities. Because no DO data were collected before the Kissimmee River was channelised, reference conditions for DO were derived from data for seven, relatively unaltered, blackwater, south Florida streams (Colangelo & Jones, 2005a) (Table 1). Each stream had at least 11 samples collected over a minimum of 1 year and some streams were sampled for more than 10 years. All reference streams are located within 145 km of each other and within 65 km of the Kissimmee River. Each reference stream has a low gradient (<6.5 cm km^{-1}) and a mean water temperature between 21.4 and 25.0 °C. The chemical characteristics of these streams also are similar. Based on data from these streams, mean DO concentrations in the Kissimmee River were expected to increase from <2 to 3–6 mg L^{-1} during the wet season and from 2–4 to 5–7 mg L^{-1} during the dry season.

Field measurements

Oxygen concentration (mg L^{-1}) and water temperature (°C) were measured at four stations within the river channel of the Kissimmee River before and after flow was restored as part of Phase I of the project. Stations were either fixed platforms that extended into the river channel from the river bank or floating buoys anchored within the river channel. At all stations, YSI 600 series multiparameter water quality sondes (YSI Inc., Yellow Springs, OH, U.S.A.) with Rapid Pulse Clark-type DO sensors, were placed 1 m below the water surface (approximately the mid-point in the water column) in the centre of the river channel. The sondes were maintained and calibrated weekly. DO and temperature were measured at two stations from 1 January 1998 to 30 September 2003 except during the construction period (1 June 1999 to 1 February 2001). Two additional stations were monitored from 1 February 2001 to September 2003. Data were recorded at 15-min intervals, averaged by hour and divided into prerestoration (1 January 1998 to 1 May 1999) and postrestoration (1 February 2001 to 30 September 2003) sampling periods. Average diel DO and temperature curves were generated for each station by month. For example, DO values measured at 06:00 hours each day during the month of January were averaged to produce a mean DO value for that hour. The same procedure was followed for each hour of the day to produce an average 24-h DO curve for the month.

Daily river channel stage data were recorded at surface water wells using automated stage recorders interfaced with Campbell Scientific CR10 data loggers (Campbell Scientific Inc., Logan, UT, U.S.A.). Wells were located at or near each DO sampling station. Stage recorders were calibrated monthly using a depth-to-water tape measure and previously surveyed elevation data. Discharge was recorded near each station several times per month using an Acoustic Doppler Current Profiler (RD Instruments 1200 kHz and 600 kHz; Workhorse Rio Grand Acoustic Doppler Current Profiler, RD Instruments, San Diego, CA) mounted on an aluminium Jon-boat, Sea Ark Boats, Monticello, AR. Water samples were collected near each station bimonthly at a depth of 0.5 m with a Van Dorn bottle and analysed for chlorophyll *a* (APHA, AWWA & WEF, 1992, 10200H 1–2), NO_2 and NO_3 [dissolved inorganic nitrogen (DIN)] (APHA, AWWA & WEF 1992, SM4500NO3F), soluble reactive phosphorus (SRP) (APHA, AWWA & WEF, 1992, SM4500PF) and dissolved organic carbon (DOC) (USEPA, 1983, Method 415.1).

Diffusion

Prerestoration diffusion was estimated using the 'dome' method (Copeland & Duffer, 1964), which is useful for measuring diffusion in lentic systems such as the prerestoration Kissimmee River channel. However, because diffusion measurements were not actually collected during the prerestoration period, a reference area that represented prerestoration diffusion conditions was chosen as a surrogate. The reference area was located in a section of the Kissimmee River channel that had not been impacted by restoration activities. Measurements were taken on at least one day each month for 14 months during February 2001 to August 2003. The 'dome' method involved a clear plastic dome (volume = 22 L; surface area = 0.16 m^2) equipped with a YSI 600 series multiparameter water quality sonde (YSI Inc.) suspended within the dome, which recorded both oxygen concentration in the air and air temperature. The dome was then floated on the water surface. Changes in the oxygen concentration within the dome were recorded every 15 min. A second sonde recorded DO and temperature within the water column beneath the dome at the same time interval. Changes in oxygen concentration within the dome were attributed to diffusion through the air–water interface. The oxygen saturation deficit in the water beneath the dome was used to determine the gas transfer coefficient so metabolism measurements could be corrected for oxygen diffusion. Diffusion measurements were only made at night to avoid errors associated with solar heating of the air within the dome and to eliminate errors from photosynthetic oxygen production during daylight hours (Copeland & Duffer, 1964; USGS, 1987).

The energy dissipation model (Tsivoglou & Neal, 1976) was used to estimate postrestoration diffusion because turbulence is the major factor controlling diffusion in lotic systems. For the energy dissipation model, the equation $K_{2(20°C)} = K'(\Delta H/\Delta X)V$, where $\Delta H/\Delta X$ is the slope expressed as m 1000 m^{-1}; V, velocity in m s^{-1} and K' varies with stream flow was used. A table for estimating K' can be found in APHA, AWWA & WEF (1992) and Bott (2006). $K_{2(20°C)}$ has the unit day^{-1}.

Metabolism

Metabolism estimates corrected for diffusion were calculated with a computer program (Stephens & Jennings, 1976) that uses the single station oxygen curve method (Odum, 1956; Odum & Hoskins, 1958; Bott, 2006). Daytime respiration was assumed to be equal to night respiration (Bott, 2006). A possible source of error in metabolism estimates can be periods of time when water column DO concentrations are not homogenous. A clinograde oxygen curve occurred during the months of May and June 1998–1999, therefore, data from these months were discarded. Photo-oxidation of DOC, which consumes oxygen during the reaction, also can introduce small errors (underestimates) in GPP (Miles & Brezonik, 1981; Edwards & Meyer, 1987). GPP (g O_2 m^{-2} day^{-1}), CR (g O_2 m^{-2} day^{-1}) and net daily metabolism (NDM) (g O_2 m^{-2} day^{-1}) were calculated for each station by month. The single station oxygen curve method assumes that changes in oxygen concentration are similar throughout the stream reach (USGS, 1987; Bott, 2006) and this was assumed to be true for the Kissimmee River.

Data analysis

Statistical analyses were performed using SAS version 8.02 (SAS Institute Inc., Cary, NC, U.S.A.). A *t*-test was used to compare DO concentrations, GPP, CR, NDM and reaeration as well as selected environmental variables before and after restoration of flow. Seasonal variability of metabolism parameters was analysed by comparing wet and dry season values (*t*-test). All statistics were considered significant at the $P < 0.05$ level.

Results

Mean DO concentrations were higher postrestoration than during the prerestoration period (*t*-test, $P < 0.01$) and postrestoration concentrations were within the target range derived from reference streams for both wet and dry seasons (Fig. 2; Table 2). Mean prerestoration DO concentrations were 1.88 mg L^{-1} which increased to 4.70 mg L^{-1} after flow was restored to the river channel. Mean seasonal diel oxygen curves were more variable after restoration of flow. Oxygen curves were similar among all stations on any given date,

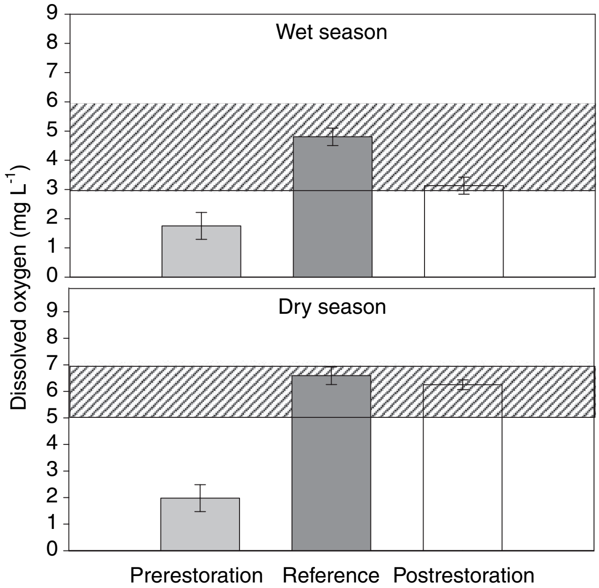

Fig. 2 Mean (± SEM) dissolved oxygen (DO) concentrations in the Kissimmee River before and after restoration and in free-flowing south Florida reference streams during the wet (June to November) and dry (December to May) season. Cross-hatched area represents the expected range of DO concentrations in the Kissimmee River after restoration.

indicating that the single station oxygen curve method was appropriate for this study (USGS, 1987). Diel temperature fluctuations were <1 °C during the prerestoration period and varied from 1–2.5 °C post-restoration.

Discharge in the remnant river channel usually was zero during the prerestoration period because most of the flow in canal C-38 did not enter the shallower remnant river channels. Discharge within the restored river channel varied between 9.25 and 70.00 m^3 s^{-1} postrestoration (Table 2; Fig. 3). Mean postrestoration chlorophyll *a* concentrations were higher than prerestoration concentrations (*t*-test, $P < 0.001$). Mean DOC concentrations were 22.0 and 20.7 mg L^{-1} before and after restoration of flow, respectively and mean reaeration coefficients increased from 0.03 day^{-1} or less before restoration to 0.41 day^{-1} postrestoration (*t*-test, $P < 0.001$) (Table 3). Dissolved inorganic nitrogen concentrations decreased slightly after restoration of flow and SRP concentrations were similar during the pre- and postrestoration periods (Table 2).

Mean annual GPP increased significantly after restoration (3.95 g O_2 m^{-2} day^{-1}) relative to the prerestoration period (0.43 g O_2 m^{-2} day^{-1}) (*t*-test, $P < 0.001$) (Table 3). Mean GPP was slightly higher

Table 2 Water quality and environmental parameters before and after restoration of flow in the Kissimmee River (±1 SEM) (dry season = December to May, wet season = June to November)

	Prerestoration			Postrestoration		
	Annual	Dry season	Wet season	Annual	Dry season	Wet season
DO (mg L^{-1})	1.88 ± 0.34	1.98 ± 0.51	1.75 ± 0.46	4.70 ± 0.24	6.25 ± 0.18	3.13 ± 0.29
Water temp (°C)	22.2 ± 1.1	19.1 ± 0.7	26.2 ± 1.1	25.0 ± 0.5	22.2 ± 0.6	27.8 ± 0.4
Discharge* (m^3 s^{-1})	0.00–3.35	0.00–3.35	0.00–0.00	9.25–73.19	9.25–62.73	13.57–73.19
Flow velocity* (m s^{-1})	0.00–0.08	0.00–0.08	0.00–0.00	0.15–0.70	0.15–0.53	0.19–0.70
Chlorophyll *a* (μg L^{-1})	9.6 ± 2.2	8.4 ± 3.4	11.1 ± 2.8	16.5 ± 0.6	14.9 ± 1.0	18.1 ± 0.7
DOC (mg L^{-1})	22.0 ± 1.7	21.4 ± 2.4	22.8 ± 2.6	20.7 ± 0.3	20.8 ± 0.2	20.6 ± 0.7
DIN (mg L^{-1})	0.14 ± 0.05	0.19 ± 0.08	0.05 ± 0.03	0.05 ± 0.01	0.06 ± 0.01	0.05 ± 0.01
SRP (mg L^{-1})	0.03 ± 0.00	0.02 ± 0.00	0.03 ± 0.01	0.02 ± 0.00	0.02 ± 0.00	0.02 ± 0.00

DIN, dissolved inorganic nitrogen; DO, dissolved oxygen; DOC, dissolved organic carbon; SRP, soluble reactive phosphorus.
*Range.

during the wet season than during the dry season for the entire study. Postrestoration mean monthly GPP was more variable than during the prerestoration period, ranging from 1.58 to 13.00 g O_2 m^{-2} day^{-1} with higher values occurring during the wet season (Fig. 3). Mean annual CR values also were higher after restoration of flow (9.44 g O_2 m^{-2} day^{-1}) than during the prerestoration period (1.61 g O_2 m^{-2} day^{-1}) (*t*-test, $P < 0.001$) (Table 3). Prerestoration CR was similar during the wet and dry season. After flow was restored to the river channel, mean CR values during the wet season increased to nearly three times greater than dry season values (Table 3). Mean P/R was 0.29 during the prerestoration period and increased to 0.51 postrestoration. Production to respiration ratios usually were <0.4 during the prerestoration period and ranged from 0.17 to 0.79 postrestoration (Fig. 3). Wet season and dry season P/R values were similar during the prerestoration period, but postrestoration P/R was higher during the dry season than during the wet season. NDM was greater during postrestoration (−5.51 g O_2 m^{-2} day^{-1}) than during the prerestoration period (−1.22 g O_2 m^{-2} day^{-1}) (*t*-test, $P < 0.001$) (Table 3). Wet season NDM was greater than dry season NDM before and after restoration of flow through the river channel and monthly variation in NDM was greater postrestoration than during the prerestoration period (Fig. 3).

Discussion

Backfilling of the C-38 canal and restoration of flow through the reconnected river channel resulted in major changes in the system. Large amounts of organic deposition were scoured from the bottom of the reconnected, flowing river channel, mats of floating aquatic vegetation that had encroached upon the open water of the river channel were reduced and much of the historic floodplain in the project area was inundated at times.

Restoration of flow to the river channel resulted in an increase in river channel depth because of increased water elevations from backfilling of the flood control canal and scouring of organic sediments from the bottom of the river channel. A portion of the increase in metabolism estimates observed after flow was restored can be attributed to the deeper channel. Increased depth of the river channel after restoration of flow accounted for approximately 24% of the increase in annual metabolism.

Dissolved oxygen

Restoration activities resulted in higher DO concentrations, more variable diel oxygen patterns and higher reaeration coefficients than during the prerestoration period. Increased flow velocity is likely the main factor driving the observed increase in reaeration coefficients and DO concentration. In flowing waters, interior water with a high oxygen deficit rapidly replaces oxygen saturated water at the surface. This process stimulates rapid reaeration of the entire volume of water (Liu & Fok, 1983). The surface renewal rate is dependent on the degree of turbulent mixing, which is mainly controlled by flow velocity and water depth (O'Connor & Dobbins, 1956). Discharge and flow velocity increased substantially during the postrestoration period (Table 2). Reaeration

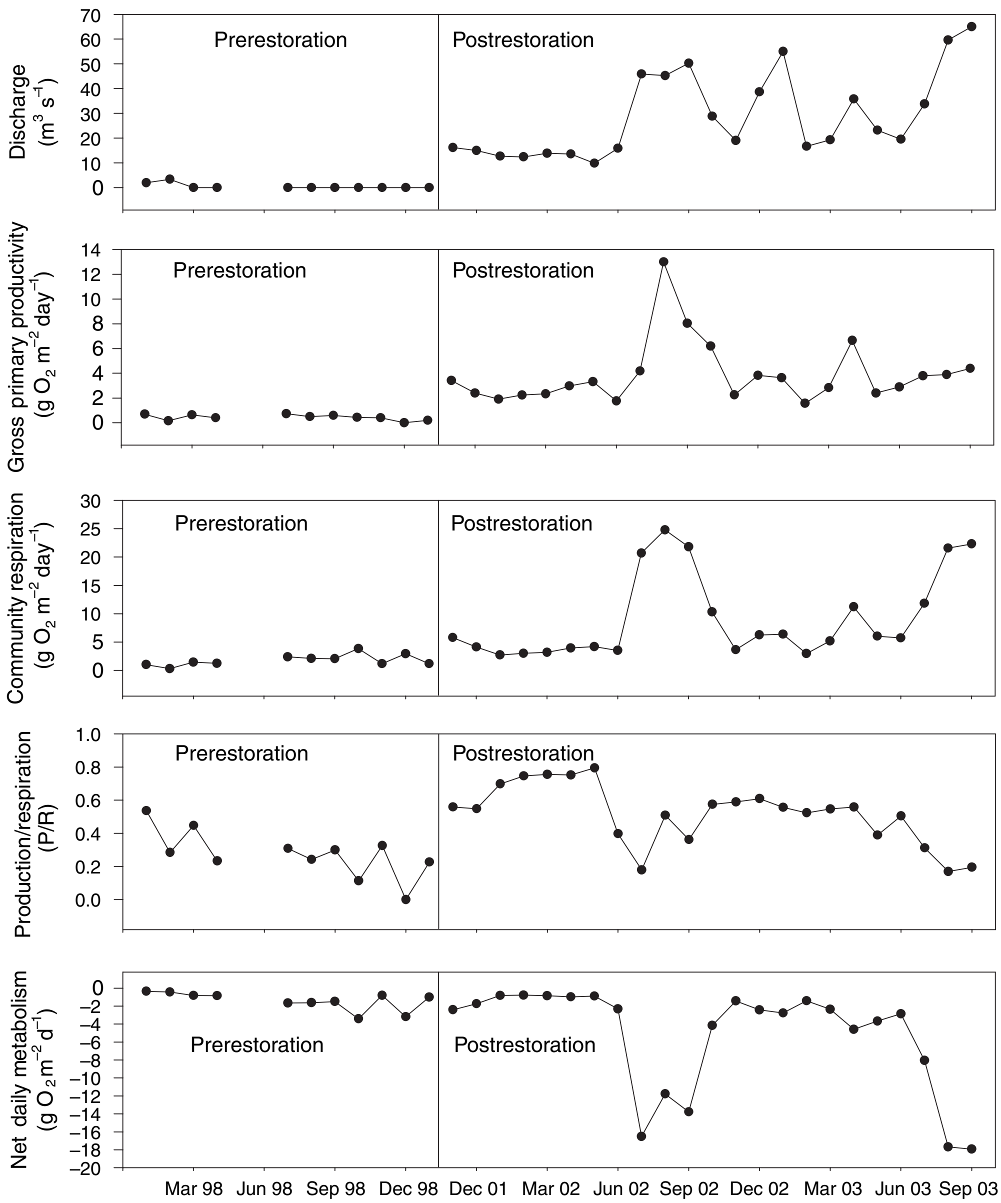

Fig. 3 Mean monthly discharge, gross primary productivity, community respiration, production to respiration ratio and net daily metabolism (GPP–CR) in the Kissimmee River.

coefficients for the postrestoration Kissimmee River were lower than those observed on the Little Tennessee River (McTammany *et al.*, 2003) and Ogeechee River, GA (Edwards & Meyer, 1987) (Table 3). However, this can likely be attributed to the steeper gradient and thus higher mean flow velocity of these rivers compared with the Kissimmee River. DO concentrations for the postrestoration Kissimmee River were within the target ranges derived from reference streams in south Florida. Although restoration of the Kissimmee River is not complete, meeting the success criteria for DO is evidence that the restoration project is on the correct trajectory.

Metabolism

Gross primary productivity in the river channel was consistently higher and more variable during postrestoration than during the prerestoration period and seasonal variation in GPP was especially evident

Table 3 GPP, CR, NDM (g O_2 m^{-2} day^{-1}), P/R values, reaeration coefficients, width and depth of rivers in the southern United States with similar characteristics to the Kissimmee River

River	Sampling period	GPP	CR	P/R	NDM	K_2 (d^{-1})	Width (m)	Depth (m)	Reference
New Hope Creek, NC	Annual	0.8	1.3	0.7	0.62	–	10	0.5	Hall, 1972
Neuse River, NC	May–October	0.29–9.8	1.68–21.5	0.2–0.7	–	–	–	–	Hoskin, 1959
Black Creek, GA	August–September, May	0.1–3.6	2.3–9.6	0.02–0.4	–	–	10.1	0.9	Meyer & Edwards, 1990
Little Tennessee River, NC	May–November	0.22–6.14	0.85–7.28	–	–	3.15–9.26	17.2–40.5	0.7–1.0	McTammany *et al.*, 2003
Tombigbee River, MS	Annual	0.39–2.97	0.60–6.00	0.38–2.01	−4.83	–	–	0.6	Naimo & Layzer, 1988
Buttahatchie River, MS	Annual	0.06–0.44	0.24–1.04	0.09–0.98	−0.90 to −0.01	–	–	–	Naimo & Layzer, 1988
Rappahannock River, VA	Spring	6.08	1.82	0.83	−1.24	–	180	2.0	Hornberger, Kelly & Cosby, 1977
Ogeechee River, GA	Annual	2.22	6.7	0.3	−4.48	0.58–3.25	44	2.5	Edwards & Meyer, 1987
	Spring	1.38	6.93	0.2	−5.55	–	–	–	
	Summer	4.23	8.3	0.47	−4.07	–	–	–	
	Autumn	0.9	5.82	0.16	−4.92	–	–	–	
	Winter	1.49	5.48	0.28	−3.99	–	–	–	
Kissimmee River	Annual	0.43 ± 0.08	1.61 ± 0.23	0.29 ± 0.05	−1.22 ± 0.22	0.0–0.03	15–30	1.6	
Prerestoration (±SE)	Wet	0.52 ± 0.07	2.13 ± 0.30	0.27 ± 0.05	−1.60 ± 0.30	0	–	–	
	Dry	0.36 ± 0.13	1.20 ± 0.27	0.30 ± 0.09	−0.92 ± 0.30	0.03	–	–	
Kissimmee River	Annual	3.95 ± 0.35	9.44 ± 0.87	0.51 ± 0.02	−5.51 ± 0.67	0.18–0.80	15–30	2.2	
Postrestoration (±SE)	Wet	4.86 ± 0.61	13.91 ± 1.39	0.39 ± 0.03	−9.10 ± 1.07	0.48	–	–	
	Dry	3.04 ± 0.28	4.97 ± 0.42	0.63 ± 0.02	−1.92 ± 0.21	0.33	–	–	

P/R and NDM values are means of monthly values.

CR, community respiration; GPP, gross primary productivity; NDM, net daily metabolism; P/R, ratio of GPP/CR.

postrestoration. The increase in system GPP after restoration of flow was likely because of changes in light penetration into the water column and the limitations of the diel oxygen curve method, rather than changes in nutrient concentrations. DIN concentrations decreased slightly and SRP concentrations did not increase significantly after restoration. During the prerestoration period, 57% of the river channel surface was covered by floating and mat forming aquatic vegetation (S. Bousquin, personal communication). Production from floating aquatic plants was not represented in the GPP estimate because the diel oxygen curve method only measures oxygen production in the water column. After flow was restored, floating and mat forming vegetation covering the channel surface was reduced to 16% allowing more sunlight to enter the water column. The reduction in coverage of floating aquatic vegetation may have led to a transfer of production from emergent macrophytes to algae. One effect of this shift of production from vascular aquatic plants to algae may include an increase in the availability of higher quality food sources for consumers. Algal biomass can be considerably greater in unshaded areas than in heavily shaded areas (Wetzel, 2001) resulting in higher GPP rates in areas where more light is available. The significant increase in mean monthly chlorophyll *a* concentrations postrestoration, supports the conclusion that increased light penetration in the water column was an important factor driving increased GPP rates. Dominance of planktonic or benthic algal production could not be determined using the diel oxygen curve method but likely varied throughout the year. During periods of low discharge and low river channel stage, large mats of periphyton were observed growing on sandy bottom substrate along the edge of the river channel and on emergent vegetation in the littoral zone of the river. Phytoplankton also was observed throughout the water column during periods of low flow (D. Colangelo, personal observation).

Community respiration rates during the prerestoration period were low compared with postrestoration rates. Oxygen consumption rates increase or decrease depending on the oxygen concentration of the water (Edwards & Rolley, 1965; Edberg & Hofsten, 1973). During the prerestoration period, oxygen concentration of the water likely was rapidly depleted by respiration in the water column and within the sediments. Because the river channel was stagnant and reaeration rates were low, respiration probably slowed down as available oxygen in the water column was consumed. Postrestoration CR rates exhibited a seasonal pattern similar to GPP, with rates as much as five times higher during the warm, wet season than during the cooler, dry season (Fig. 3). It is likely that microbial oxygen consumption increased with warmer water temperatures during the wet season, resulting in higher CR rates (Bott *et al.*, 1985; White *et al.*, 1991; McKnight *et al.*, 1993).

Higher postrestoration P/R values indicate that restoration of flow resulted in an increase in autotrophic processes within the system. However, P/R values from the restored section of the Kissimmee River show that it is moderately heterotrophic. Heterotrophy of the postrestoration Kissimmee is a result of high CR rather than low GPP. NDM was negative during the prerestoration period and significantly more negative after flow was restored. During the prerestoration period, the river channel and canal-drained floodplain rarely interacted because river stage was seldom high enough to overtop the channel banks. Decomposing floating and emergent vegetation present in the river channel were probably more important than carbon inputs from the surrounding floodplain and watershed during the prerestoration period. During postrestoration, most of the in-channel aquatic vegetation and organic sediments were flushed out of the river channel and transported downstream as flow was restored. Although these carbon sources were to a large extent no longer available, system metabolism increased significantly. Interaction between the river and floodplain occurred frequently during the postrestoration period which likely led to increased carbon inputs from the floodplain. After flow was restored, floodplain carbon sources almost certainly became more important than in-channel carbon sources such as organic sediments composed of decaying floating and emergent aquatic vegetation.

Comparison with other rivers

Prior to restoration, metabolism in the Kissimmee River was low relative to measurements in other southeastern U.S.A. studies (Table 3). However, following restoration, metabolism values from the Kissimmee River were similar to values reported for other rivers of the southern U.S.A. in general and other blackwater systems of the southeast in particular. The Ogeechee River is a relatively unpolluted, low gradient, blackwater river in southern Georgia, which is representative of medium order blackwater rivers in the southeastern U.S.A. (Edwards & Meyer, 1987) and is similar in size, chemistry and climate to the prechannelisation Kissimmee River. Edwards & Meyer (1987) reported annual GPP rates for the Ogeechee River that were lower than rates observed for the postrestoration Kissimmee River, however, during summer, GPP rates in the Ogeechee River were similar to wet season (summer) GPP in the Kissimmee River. Rates of GPP varied seasonally in both systems with higher GPP occurring during the summer when water temperatures were warm. Mean annual postrestoration Kissimmee River CR rates were generally similar to mean annual CR rates for the Ogeechee River (Table 3). However, CR rates for the Kissimmee River increased significantly during the warm, wet season while CR rates for the Ogeechee River remained stable throughout the year. Edwards & Meyer (1987) concluded that high CR rates in the Ogeechee River during the winter were likely the result of increased microbial respiration stimulated by large inputs of organic matter from the floodplain during high water periods. CR rates for the Kissimmee River peaked during July to September. These peak CR rates coincided with floodplain inundation that almost certainly resulted in the transport of organic matter from the floodplain into the river channel. It is possible that high respiration rates observed in the Kissimmee River during the wet season also were related to increased organic matter loads from the floodplain and increased microbial respiration. Black Creek, a blackwater stream and a tributary of the Ogeechee River also had metabolism rates that were similar to the postrestoration Kissimmee River (Meyer & Edwards, 1990). Similarities between metabolism values from the postrestoration Kissimmee River and relatively pristine blackwater rivers of the coastal plain, suggest that restoration activities have resulted in a more natural river system.

Conclusion

Backfilling of flood control canal C-38 and restoration of flow through reconnected river channels increased DO concentrations and reaeration rates. The increase in reaeration, which was driven by higher flow velocity during postrestoration, was probably the most important factor contributing to the increase in DO. GPP was higher and more variable after flow was restored to the river channel than during the prerestoration period. The main factor contributing to increased GPP was likely reduced shading of the water column by floating and mat forming aquatic macrophytes, which in all probability, allowed for increased algal production. CR rates also were higher postrestoration than during the prerestoration period. Increased CR rates can be attributed to warm water temperatures and higher concentrations of DO available for respiration. Postrestoration P/R ratios were higher than during the prerestoration period signifying an increase in autotrophic processes after flow was restored to the river channel. Postrestoration NDM values indicated an increase in the amount of organic matter being processed. During the prerestoration period, the most plentiful carbon source was in-channel organic sediments, which were largely flushed away after flow was restored. This suggests that the most plentiful carbon source after restoration of flow was organic matter that entered the river channel from the reconnected floodplain.

Metabolism parameters measured during postrestoration were generally similar to those measured on the Ogeechee River, a relatively pristine, low-gradient, blackwater river. In addition, DO concentrations for the postrestoration Kissimmee River were similar to DO concentrations for seven minimally impacted reference streams. Although the Kissimmee River restoration project is not yet complete, results from this study show that restoration efforts are on the proper trajectory. Future phases of the restoration project include backfilling an additional 23 km of canal and reconnecting 45 additional kilometres of river channel as well as managing the system using a more natural hydroperiod. Once restoration is complete, river metabolism should be reevaluated and compared with the results of this study to determine if changes in the system have stabilised. Thereafter, metabolism data can be used to monitor the effects of changes and disturbances in the system over time.

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