Environ Biol Fish (2018) 101:997–1009
https://doi.org/10.1007/s10641-018-0754-y

Movement response of Orange-Vaal largemouth yellowfish (*Labeobarbus kimberleyensis*) to water quality and habitat features in the Vaal River, South Africa

T. Ramesh · Colleen T. Downs · Gordon C. O'Brien

Received: 16 March 2017 / Accepted: 1 April 2018 / Published online: 13 April 2018

Abstract Many threatened fish species that utilize riverine habitats are faced with habitat degradation and subsequent deterioration in their ecological surroundings. Habitat degradation is a consequence of water quality parameters associated with anthropogenic activities including mining, industrial, agricultural and urban activities. We examined how the movement behaviour of radio-tracked Orange-Vaal largemouth yellowfish (*Labeobarbus kimberleyensis)* responded to a suite of water quality chemical parameters and habitat features in the Vaal River, South Africa. We found that the probability of their movement increased with a decrease in water clarity, presence of emergent and overhanging marginal vegetation and fast flowing rapids. High mobility in conditions of low water clarity was probably related to low prey capture success of this piscivorous fish. High movement of largemouth yellowfish in emergent and overhanging marginal vegetation areas and rapid habitat biotopes were attributed to accessibility of prey within these important cover features. When water quality parameters were considered, the probability of largemouth yellowfish movement increased with increasing levels of dissolved chloride (Cl) and silicon (Si), whereas movement decreased with high phosphate (PO_4) concentrations and increased with alkalinity levels in the river. High nutrient levels associated with eutrophication caused reductions in the movement of largemouth yellowfish. The association of increased movement of largemouth yellowfish with increasing Cl and Si is indicative of degraded habitat condition in the Vaal River system. Our study showed the importance of monitoring fish behavioural movement patterns to multiple environmental parameters, as these fish are important ecological indicators when appropriate conservation and management plans of freshwater ecosystems are required.

Keywords Ecosystem indicator · Freshwater ecosystem · Radio telemetry · Environmental parameters · Vaal River · South Africa

Introduction

An important factor of environmental monitoring is determining how water quality, physical habitat and other anthropogenic disturbances affect the behaviour and physiology of organisms (Aparicio and Sostoa 1999; Harvey et al. 1999; Gilliam and Fraser 2001; Harrison and Whitfield 2004). Fish are considered as one of the best ecological indicators of freshwater ecosystem health as they exhibit distinct behavioural, physiological and morphological responses to environmental stressors (Cooke and Cowx 2004; Harrison and Whitfield 2004, 2006; Elliott et al. 2007). Monitoring

T. Ramesh · C. T. Downs (✉) · G. C. O'Brien
School of Life Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg, KwaZulu-Natal 3209, South Africa
e-mail: downs@ukzn.ac.za

T. Ramesh
Sálim Ali Centre for Ornithology and Natural History, Anaikatty Post, Coimbatore 641108, India

the movement patterns of aquatic organisms, such as fish, can offer an intuitive understanding of their distribution as well as tolerance to associated environmental conditions (Fausch et al. 2002; Gowan and Fausch 2002; Albanese et al. 2004; Petty and Grossman 2004; Gowan 2007; Roberts and Angermeier 2007). Thus, this knowledge could improve our understanding of river fish ecology amidst increasing anthropogenic impacts worldwide (Gowan et al. 1994; Roberts and Angermeier 2007).

Locomotion of fish is a dynamic biological process indicating the general health and physiological response of fish (Schreck et al. 1997; Cooke et al. 2003). In fish species, chronic exposure to multiple stressors reduces swimming ability, growth and habitat condition which may impair fish health and possibly result in mortality (Bervoets and Blust 2003; Wepener et al. 2011). In aquatic ecosystems the evaluation of excessive movement of species beyond normal ranges is challenging but studies have shown that it can be determined using movement rate (Gerhardt 2007). Excessive anthropogenic effects reduce fitness and survival potential in many species (Brind'Amour and Lobry 2009). Fish health is influenced by poor water quality, accumulation of heavy metals/ toxicants and alteration in habitat structure from polluted environments (Gerhardt 2007). The movement responses of specialist species to environmental pollutants can affect physiology, produce physical abnormalities and lead to mortalities (Gerhardt 2007; Brind'Amour and Lobry 2009). The first response to excessively stressful environments may include avoidance of non-optimal conditions, followed by physiological stress where respiratory, metabolic or excretory rates may increase (Dallas and Day 2004). Telemetry techniques allow fish tracking in response to environmental stressors (Lucas et al. 1993; Cooke et al. 2003; O'Brien et al. 2012a, 2013a, b). Considering the importance of movement processes, studies have linked movement of freshwater river fish to ecological factors such as physical features, habitat structure and chemical variables (Gowan et al. 1994; Gilliam and Fraser 2001; Gerhardt 2007).

Multiple physico-chemical variables including water clarity, depth, pH, salinity, conductivity, nutrients, organic enrichment, trace metals and other toxicants, flow and habitat structure potentially influence the wellbeing of aquatic ecosystems (Dallas and Day 2004; Villiers and Thiart 2007; Monette and McCormick 2008; Wepener et al. 2011). In South Africa, a large proportion of river basins (60%) have been exposed to habitat destruction (Revenga et al. 2005), affecting their primary functions and services including nutrient recycling, waste purification and maintaining large biodiversity (Palmer et al. 2005; Revenga et al. 2005). In particular, the Vaal River is located in the main mining and industrial areas of South Africa (Wepener et al. 2011). In the past, the water quality in this river has decreased significantly due to mixing of run-off waste such as salt load, nutrients and agriculture pesticides from the metropolitan area leading to mass mortality, particularly of yellowfish species (*Labeobarbus* spp.) which are habitat specialists in the Vaal River system (McCarthy et al. 2007; Villiers and Thiart 2007; McCarthy and Pretorius 2009; Wepener et al. 2011). The health of aquatic ecosystems can be studied using biological indicators such as socially and economically important apex predators, like the Orange-Vaal largemouth yellowfish (*Labeobarbus kimberleyensis)* (hereafter referred to as largemouth yellowfish), as they are sensitive to environmental changes (O'Brien et al. 2011, 2013a, b).

The largemouth yellowfish is an endemic and a high priority conservation species in South Africa region (Impson et al. 2008). It is one of the largest cyprinid fish in southern Africa. Moreover, the IUCN has categorized this species as "Near Threatened" (Impson and Swartz 2007) primarily due to reduction in its habitats and population size in its distribution range, and its sensitivity to flow modifications and poor water quality (Impson and Swartz 2007; Skelton and Bills 2007; De Villiers and Ellender 2008; Impson et al. 2008; DWA 2010; Ellender et al. 2012). In particular, the rapid biotope habitat (rapidly changing water flow) can also change the movements of fish as they find inaccessible habitats or find refuge from high current velocities (Albanese et al. 2004; O'Brien et al. 2013a, b). Previous studies have mainly focused on largemouth yellowfish habitat utilization (O'Brien et al. 2011, 2013a, b) but none on evaluating their movement response to water quality and habitat change. To fill this knowledge gap, we aimed to understand the movement behaviour of this species according to a suite of water quality and habitat features. We hypothesised that movement behaviour largemouth yellowfish in the Vaal River, South Africa, is influenced by a suite of water quality chemical parameters and habitat features, though in different ways. Based on this we had the following predictions:

- that high yellowfish activity/movement occurs where they are more likely to find prey species within a range of habitats such as emergent and overhanging marginal vegetation in the littoral zone and bank of the river where they can presumably meet their resource needs.
- that yellowfish movement rates would increase as water clarity declined as this may reduce the feeding ability of piscivores such as yellowfish.
- that yellowfish movement rate may increase within the rapid biotope which allow them to exploit previously inaccessible habitats or find refuge from high current velocities.
- that yellowfish will increase their movement to increasing water conductivity while increased nutrient loading can lead to elevated ammonia and nitrite concentration which are toxic to many aquatic organisms and such nutrient enrichment can lead to a rapid numerical increase in fast-growing plant, thus reducing fish movement (Herbert and Steffensen 2005; Zhang et al. 2012).

Materials and methods

Study site

The Vaal River (upstream, 26°54′0.99”S; 27°26′45.39″ E; downstream, 27°41′55.93"S; 26° 5'22.31"E, Fig. 1) is one of Africa’s most important rivers providing water supply to Gauteng Province, the economic heartland of South Africa, supporting 42% of the urban population in the region (Braun and Rogers 1987). The river rises on the Drakensberg escarpment and flows ~900 km to the confluences with the Orange River (Braun and Rogers 1987; Bertasso 2004, Fig. 1). In South Africa, the catchments of the Vaal River spans approximately 192,000 km^2 and it is exposed to discharges from gold and coal mines, industry and sewage-treatment plants (DWA 2010; Wepener et al. 2011). Also, construction of weirs, dams/ impoundments and small manmade lakes has altered the natural water flow (Wepener et al. 2011). Our study was done in a reach of the middle Vaal River, southwest of Johannesburg (Fig. 1), on a 190 km section from Parys to upstream of Bothaville (Fig. 1). The study area is characterised by a sequence of moderately deep <3 m mud and sand dominated pools with intermittent shallow >1 m cobble, boulder and bedrock dominated rapid habitats. The slight gradient of the reach ranges between 0.2% to 0.6% which results in velocities between 0 and 1.5 m/s. The study area is under high anthropogenic pressures which have local impacts on water quality, habitat quality, and river flow (DWA 2010; Wepener et al. 2011; O'Brien et al. 2013a). For the study area details, see O’Brien et al. (2013a, b). The area receives summer rainfall and mean annual rainfall of ~500 mm to 600 mm.

Study species

In this riverine system, the largemouth yellowfish is considered an apex predator that reaches over 20 kg. It primarily occurs in deep pools of large rivers and also in slow-moving water upstream sections of weirs and structures (De Villiers and Ellender 2007; Ellender et al. 2012). This apex predator, initially feeds on insects and small crustaceans as a juvenile, then when larger in size it is a more carnivorous and opportunistic hunter (O’Brien and De Villiers 2011).

Data collection

In total, 27 adult largemouth yellowfish were captured using gill netting, fyke trapping and electrofishing (boat-mounted electrofisher (1 kV) techniques (O’Brien et al. 2013a, b). Fishing effort for gill nets (93 mm mesh, 25 m length nets) was two nights for 12 h, five 12 h night efforts deployed in the evening and early morning for large fyke net traps (22 mm mesh with two 35 m wings), and purse dragged eight times for a large seine net (22 mm mesh, 35 m length). Every fish was tagged with radio transmitters (Weight 20 g; Advanced Telemetry Systems Inc. (ATS), Isanti, MN, USA) resulting in a tag burden of 2% of their body mass. Each captured largemouth yellowfish was anaesthetised by placement in a 50 L water filled container with either 2-phenoxyethanol (0.4 mL/L) or clove oil (0.1 mL/L) added. We attached transmitters dorso-laterally through the musculature just below the dorsal fin using stainless steel wire [see detailed tagging procedure in O’Brien et al. (2013a, b)]. We injected an antibiotic (Terramycin® containing oxy-tetracycline) (1 ml/kg) and applied Betadine (Mundipharama, RSA) on touched areas of the fish and wound-care gel (Aqua Vet) on wounds to treat and minimize their risk of

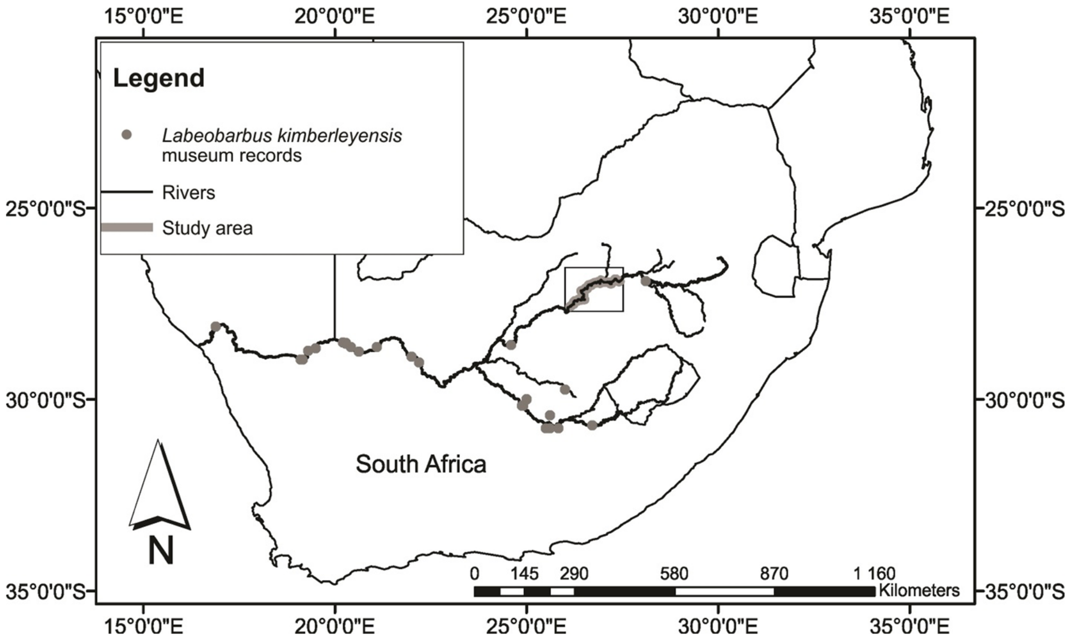

Fig. 1 Map of the survey regions showing the distributions of largemouth yellowfish *Labeobarbus kimberleyensis* (LKIM) on the Vaal River, southern Africa

infections. The total body length, fork length, girth length (mm) and body weight (g) were recorded from each tagged yellowfish and it was placed in circulating water within a 50 L water container until it recovered completely. Immediately after recovery, fish were released back into the river at the place of capture. All the capture and handling procedures of fish were followed using standard ethical guidelines of North West University, South Africa (O'Brien et al. 2012a, 2013a, b).

We monitored tagged individuals using various techniques including foot walks along the banks of the Vaal River, small inflatable boats, and by air in a fixed wing aircraft (O'Brien et al. 2012a; 2013a, b; Fig. 2) from July 2007 to August 2010. We used only behavioural data collected after two weeks of release, although tagged largemouth yellowfish were monitored immediately to make sure there was survival and recovery from the tagging procedures (Bridger and Booth 2003; Rogers and White 2007). We carried out random and dedicated continuous 24-h surveys and the global positions of the tagged largemouth yellowfish (± 1 m accuracy) were recorded using a detailed georeferenced map of the site/hand-held global positioning system (GPS, eTrex (Garmin, Kansas City, USA), or GeoExplorer® 3000 Trimble (Trimble Navigation Ltd., Sunnyvale, CA, USA). Surveys were conducted for 3–4 days per month in a specific section of the river to cover the entire study area for a year from the date of release. Individual fish were identifiable based on their unique radio transmitter signals visible on our computer/mobile system. We measured the total maximum movement distance of a tagged largemouth yellowfish during four consecutive 10-min intervals after locating the tagged fish. The movement categories were described as low (<10 m/10 min) and high movement (≥10 m/10 min). We evaluated activity: (feeding/non feeding), fish habitat cover (emergent and overhanging marginal vegetation, aquatic vegetation, boulders/rocks (merged boulders/rocks) and undercut banks (roots and dead/submerged trees), biotope (backwater areas, pools, glides, and rapids (riffles/runs), water column depth (mm) measured with a depth stick, water clarity (m) measured with a clarity tube, substrate types (silt, sand, gravel, cobble, boulder, bedrock), water colour, water surface flow (no flow, barely perceptible, riffle surface, smooth turbulent, undular broken) and associated it with the movement of yellowfish (Bovee 1986; Hirschowitz et al. 2007; King et al. 2010; O'Brien et al. 2012b; 2013a, b). Water flow (cumecs m^3/s), dissolved salts (mg/l) (Ca, Cl, K, Mg, and SO_4), dissolved nutrients (mg/l), (NO_3, PO_4), dissolved toxicant (mg/l) (F, NH4), pH, alkalinity (mg/l), electrical conductivity (mS/m), and Si (mg/l) were downloaded from the Department of Water and Sanitation, South Africa Affairs for the respective study areas.

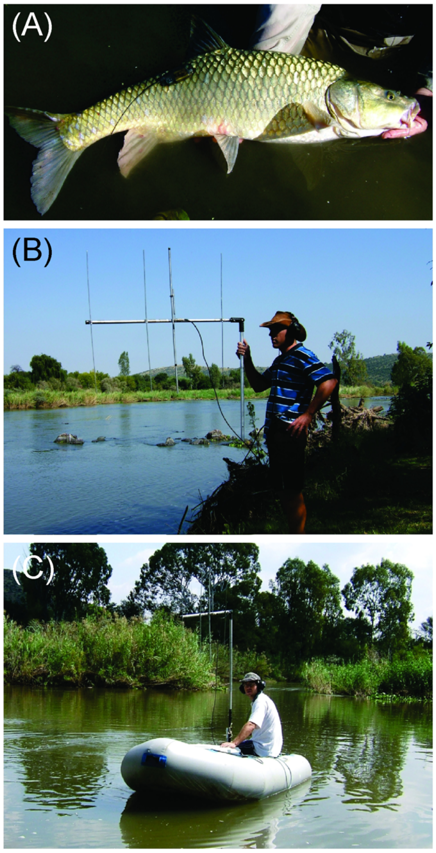

Fig. 2 Identifying the position of tagged largemouth yellowfish *Labeobarbus kimberleyensis* (**a**) by walking on the bank (**b**) and drifting in a boat (**c**) on the Vaal River, southern Africa

Data analyses

The movement was categorized as 0 or 1 if the movement was low (<10 m/10 min) or high (≥10 m/10 min) respectively. Factors associated with individual fish movement were identified using Binomial Generalised Linear Models (GLM) with mixed effects regression as a function of covariates using the lme4 package (Bates et al. 2014) in R (R Development Core Team 2014). Covariates and individual fish were used as fixed and random effects in the model, respectively. Habitat features and water quality were tested separately for their respective influence on largemouth yellowfish movement. To avoid issues with multicollinearity among predictor variables, we removed the correlated variables ($r > 0.60$) in a hierarchical approach using Pearson correlation co-efficient test (Graham 2003). First, we performed correlation tests among variables within habitat features, and water quality variables separately then retained the least correlated habitat features (activity, cover, biotope, depth, water clarity, substrate and water surface flow) and water quality variables (Cl, F, NH4, PO4, pH, alkalinity and Si) for further statistical analysis.

The best-fit candidate models with few predictors were selected based on the framework of Burnham and Anderson (2002). Depth, water clarity, Cl, alkalinity and Si were log transformed ($\log_{10}$) prior to regression, allowing model coefficients to be interpreted as the change in the log-odds ratio (Cooch and White 2005). Model fit was assessed by examining Akaike's information criterion, standardized residuals, and observed vs. predicted values (Burnham and Anderson 1998). Significance of the individual regression coefficients was evaluated at $\alpha = 0.05$ level. Models were chosen based on *p*-values (significant when $p < 0.05$) of covariates, by examining plots of residuals and using Akaike's information criterion (AIC) to compare candidate models. The best model (the model with the minimum AIC value) was used as relative measure of model rank; models with delta AIC values less than 2 suggest substantial evidence for the model (Burnham and Anderson 2002). All candidate models ranking less than 2 delta AIC were used as a guide to select the best-fit models explaining movement of largemouth yellowfish (Burnham and Anderson 2002). Estimates of the relative importance of predictor variables were made by summing the Akaike weights (wi) across all the models in which the variable occurred (Burnham and Anderson 2002). We evaluated the direction and effect of variables based on the average estimates of the parameter coefficient and its precision across the entire set of models (Burnham and Anderson 2002). All statistical analyses were done in Programme R version 3.0 (R Development Core Team 2014) using other supporting packages MASS (Venables and Ripley 2002), rJava (Urbanek 2010), glmulti (Calcagno and de Mazancourt 2010) and MuMIn (Bartoń 2013).

Results

Out of 27 largemouth yellowfish fitted with transmitters, we successfully tracked 12 individuals. The adult individual's mean morphometric data were as follows: mean body mass 3616 ± 220 g, mean total length 678 ±

14 mm, mean fork length 616 ± 12 mm and mean girth 370 ± 8 mm. The 12 tracked adult individuals resulted in 538 observations.

When we related the movement of 12 individuals to habitat features, the two best models were identified based on ≤2 delta AIC (Table 1). The relative variable importance across all the models were water clarity (wi = 1), feeding (wi = 1), habitat cover (wi = 0.96) and biotope (wi = 0.35) as main predictor variables for yellowfish movement, while the contribution of other variables was less (wi = ≤ 0.01). The coefficient estimate of the top two models was almost consistent and suggests that movement increased with decreasing water clarity ($\beta = -13.04 \pm 2.79$, $p < 0.005$), presence of feeding event ($\beta = 6.01 \pm 0.78$, $p < 0.005$), emergent and overhanging marginal vegetation cover ($\beta = 3.81 \pm 1.30$, $p = 0.003$) and rapid biotope ($\beta = 4.13 \pm 2.65$, $p = 0.120$). The movement reduced at water column but not significantly ($\beta = -2.33 \pm 1.36$, $p = 0.087$) among all habitat covers. Overall GLM mixed model coefficients showed a significant relationship between probability of largemouth yellowfish movement with water clarity, habitat cover and feeding event (Fig. 3).

The relationship between largemouth yellowfish movement and water quality was explored separately to evaluate the specific contribution of each variable. Two best candidate models were identified for probability of largemouth yellowfish movement based on the model with low AICc (≤2 delta AIC). Chloride (Cl) and PO_4 representing salt and nutrient variables were identified as two important predictors of movement across the two competing models (Table 1). However, other important variables such as Si and alkalinity were also found to influence probability of high movement across the top models. Movement increased with increasing levels of Cl ($\beta = 57.44 \pm 7.17$, $p < 0.005$) and Si ($\beta = 3.61 \pm 0.47$, $p < 0.005$) whereas movement decreased with high PO_4 levels ($\beta = -35.83 \pm 7.58$, $p < 0.005$) and increased with alkalinity levels ($\beta = -20.19 \pm 13.81$, $p = 0.144$). The relative variable contribution across all models for Cl, PO_4 nutrient and Si as predictor variables was higher (wi = 1.0 for each) than alkalinity (wi = 0.41) and F toxicant (wi = 0.32), whereas the contribution of other variables was minor (wi = ≤ 0.06). GLM coefficients showed a significant relationship between probability of largemouth yellowfish movement with Cl, PO_4 nutrient, and Si (Fig. 4).

Discussion

Globally fish species living in freshwater habitats are among the most endangered taxa on Earth (Collen et al. 2014). We found that largemouth yellowfish movements increased significantly with decrease in water clarity, presence of emergent and overhanging marginal vegetation, rapid biotope and presence of feeding events. When water quality was considered, largemouth yellowfish movement increased with increasing levels of Cl and Si whereas their movement decreased with high PO_4 nutrient load and increased with alkalinity levels in the river. In particular riverine fish species

Table 1 The top generalised linear mixed effect multi models showing the effect of habitat features and water quality variables on movement response of large mouth yellowfish *Labeobarbus kimberleyensis*

Environmental stressors	Selected models	df	logLik	AICc	delta AIC	Weight
Habitat features	Water clarity + Feeding + Available habitat	8	−112.09	240.45	0.00	0.61
	Biotope+ Water clarity + Feeding + Available habitat	11	−109.52	241.55	1.09	0.35
	Water clarity + Feeding	4	−119.57	247.22	6.76	0.02
	Water clarity + Depth + Feeding	5	−119.47	249.05	8.60	0.01
	Water clarity + Depth + Feeding + Substrate	6	−119.04	250.23	9.77	0.00
Water quality (chemical variables)	Cl + PO_4 + Si	5	−195.1	400.32	0.00	0.39
	Cl + PO_4 + Si + Alkalinity	6	−194.34	400.84	0.52	0.30
	Cl + F + PO_4 + Si	6	−195.08	402.32	2.00	0.14
	Cl + F + PO_4 + Si + Alkalinity	7	−194.29	402.79	2.47	0.11
	Cl + F + pH + PO_4 + Si	7	−194.87	403.96	3.64	0.06

df, residual degrees of freedom; logLik, Log likelihood; AIC, Delta Akaike Information Criterion; Delta AIC, the difference in AIC values between each model and the model with the lowest AIC; PO4, Dissolved Phosphorus; Cl, Chloride; Si, Silicon; F, Fluoride

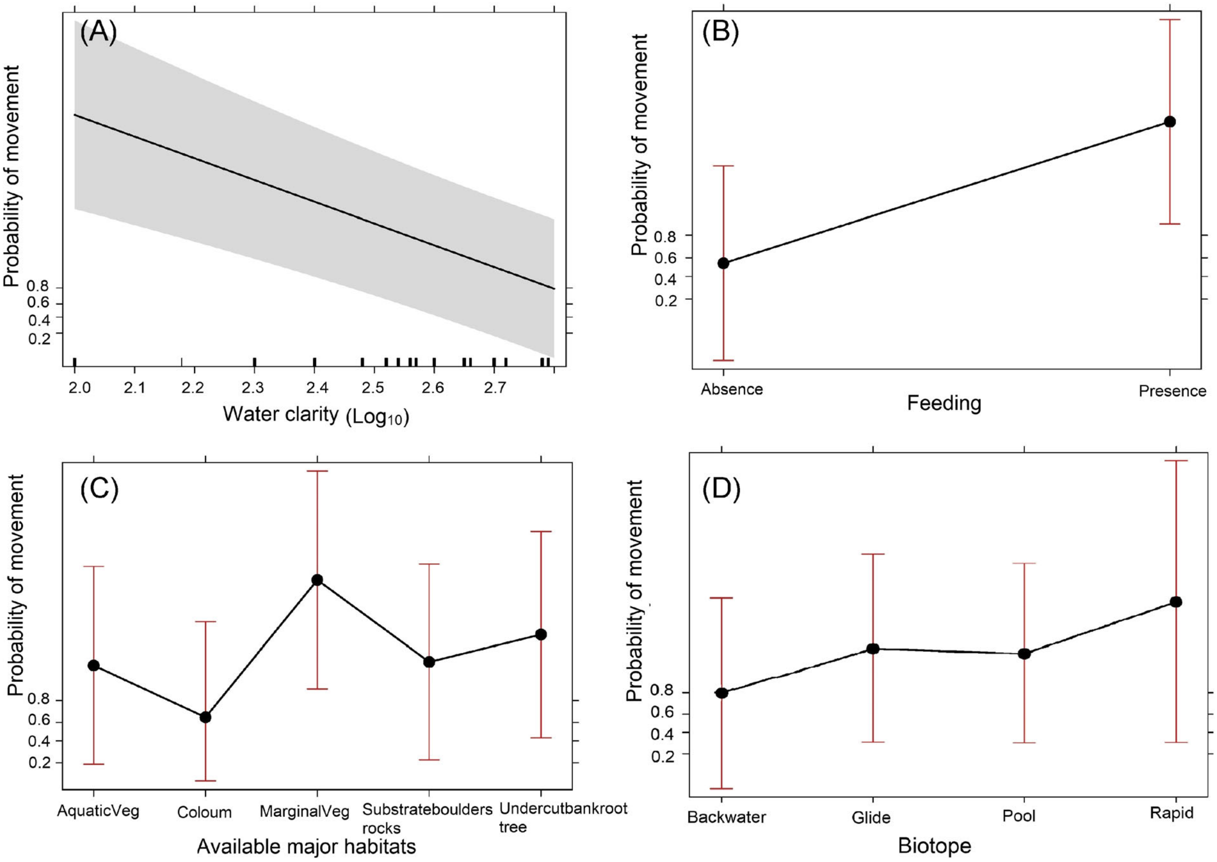

Fig. 3 Generalised linear mixed effect model (± 95% confidence intervals) explaining the predicted relationships between movement of large mouth yellowfish *Labeobarbus kimberleyensis* and covariates (water clarity (**a**), occurrence of feeding event (**b**), available major habitat (**c**) and biotope (**d**) from the best models (≤2ΔAIC)

faced with critical habitat degradation by a variety of anthropogenic disturbances, such as dam and weir construction and accumulation of heavy metals, nutrients, other chemicals from industries and urban waste, and runoff of pesticide use in the nearby agricultural land (Rahel et al. 1996; Bervoets and Blust 2003; Nilsson et al. 2005; Habit et al. 2007; Wepener et al. 2011; Cooke et al. 2012). The threatened riverine fish species such as largemouth yellowfish are more vulnerable to these impacts because of its sensitivity to degraded water quality (Impson and Swartz 2007). These detrimental effects affect fish metabolic activity, resistance to diseases, reproductive potential, and ultimately the health and survival of individual/population (Chapman 1996; Barton 2002).

Water clarity is one of the indicators of habitat condition of freshwater ecosystems (Geisler et al. 2016). Variations in water clarity influence surface temperature, heat budgets and stable environment in the freshwater system (Mazumder and Taylor 1994; Fee et al. 1996). The amount of light passing through the water column is needed for photosynthesis (Walmsley and Bruwer 1980; Dallas and Day 2004). Furthermore, poor land use practices around Vaal River causes soil erosion that leads to elevated turbidity (Mulder 1973). Consequently, turbid environments affect primary production (Maitland 1995), zooplankton production (Walmsley and Bruwer 1980), and subsequently reduces the food availability and oxygen levels for fish (Kirk and Akhurst 1984; Newcombe and MacDonald 1991). Many fish species use visual cues to select feeding sites, capture prey and escape from potential threats (Aksnes and Utne 1997; Vogel and Beauchamp 1999; Figueiredo et al. 2015). The largemouth yellowfish as a visual predator, relies on water visibility while feeding. Particularly, such turbid environment significantly decreases feeding success rates of piscivorous fish, which feed on more visible prey (Mulder 1973; De Robertis et al.

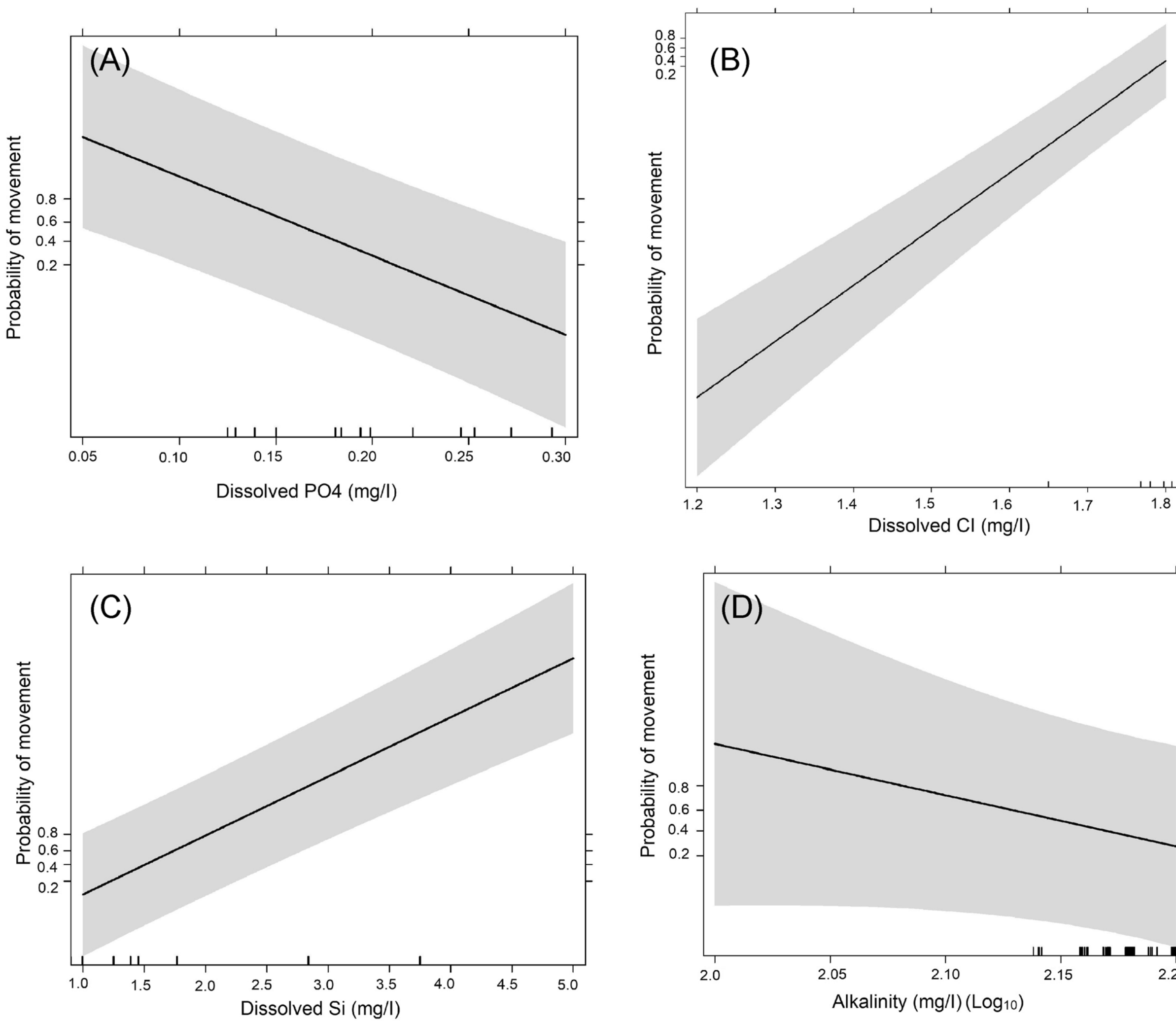

Fig. 4 Generalised linear mixed effect model (± 95% confidence intervals) explaining the predicted relationships between movement of largemouth yellowfish *Labeobarbus kimberleyensis* and covariates (dissolved Phosphate (PO_4; **a**), Chloride (Cl; **b**), Silicon (Si; **c**) and Alkalinity (**d**) from the best models (≤2ΔAIC)

2003; Figueiredo et al. 2015). Generally, low prey capture success rate increases the high mobility in fish (Gregory and Levings 1996; De Robertis et al. 2003). Therefore, the reduced feeding efficiency might have enhanced the high movement in largemouth yellowfish, and this may have an impact on the physiology of the species (Dallas and Day 2004).

We found that largemouth yellowfish movement was higher in vegetated areas. This could be due to higher availability of habitats which favours environmental quality (Gregg and Rose 1985; Schultz and Dibble 2012), emergent and overhanging marginal vegetation provides cover reducing mammal and bird predation (Uieda and Motta 2007) and can help yellowfish by avoiding exposure to sunlight, wind action, temperature variation and water flow in the freshwater system (Boss and Richardson 2002). Our study revealed high movement of largemouth yellowfish in emergent and overhanging marginal vegetation in the littoral zones and on the river bank probably because structural habitat complexity influences prey abundance and diversity (O'Brien et al. 2013a) and therefore, enforcing fish activity.

Our study found that largemouth yellowfish showed high movements when associated with the rapid biotope. This species prefers fast-flowing waters with sandy or rocky substrate (Mulder 1973; Skelton and Bills 2007) and shows strong behavioural response patterns to disrupted/sudden changes in flow (O'Brien et al. 2013a). These responses possibly involved the coordinated high movement of individuals into suitable refuge areas to avoid rapidly changing water levels/ water flow and sudden surface-associated temperature changes (O'Brien et al. 2013a). Size-selective predators such as otter *Aonyx* spp. and predatory birds preferentially consume larger fish (Matthews 1998) and an increased predation risk in fast flowing shallower areas of a river might account for the high movements of large size-classes of largemouth yellowfish.

In our study, we found low movement of largemouth yellowfish in response to high dissolved phosphorus nutrient. This was probably due to high nutrient load in the Vaal River (De Villiers and Thiart 2007; Wepener et al. 2011). Although nutrients such as dissolved phosphorus (P) and nitrogen (N) are important components for healthy aquatic ecosystems, they are of most concern because they can stimulate/limit the growth of algae and aquatic weeds that can lead to eutrophication (Graham and Wilcox 2000; Anderson et al. 2002; Nhapi and Tirivarombo 2004; Peretyatko et al. 2007; Villiers and Thiart 2007; Wepener et al. 2011; Akbarimehr et al. 2016). Consequently, the water quality can be further reduced when bacteria consume dead algae and use available dissolved oxygen and elevate ammonium levels, which hamper aquatic life (Hellawell 1986). Such environmental changes affect pH and temperature (Nhapi and Tirivarombo 2004). Therefore, hypoxic conditions reduce fish metabolic rate and movement in order to minimize energy expenditures (Schurmann and Steffensen 1994; Dallas and Day 2004; Herbert and Steffensen 2005; Zhang et al. 2009).

Elevated levels of dissolved Cl observed in the Vaal River during this study that exceeded the Target Water Quality Guideline levels of aquatic ecosystems in South Africa (DWAF 1996), increased the probability of largemouth yellowfish movement in the Vaal River during our study. Water salinity is an important natural stressor affecting aquatic communities in the freshwater ecosystem (Gutiérrez-Cánovas et al. 2009; Vidal-Abarca et al. 2013; Schriever et al. 2015). Dissolved Chloride (Cl) is one of the major ions found in most natural waters and its levels increase due to weathering of rocks, industrial and sewage effluents, and the use of chlorination processes for drinking where runoff occurs into rivers (Wannamaker and Rice 2000). Thus, these polluted aquatic systems can stimulate high movement of largemouth yellowfish. Similarly, we also found significant increase in fish movement in response to increased levels of Si. Although, Si is removed from water naturally through reverse weathering process such as plankton fixation and sediment settling of dissolved silicon with clay minerals (Tallberg 2000), high concentrations of Si can also significantly influence and limit phytoplankton communities under eutrophication (Tallberg 2000; Conley et al. 1993). Alkalinity was not a significant predictor determining the largemouth yellowfish movement in the Vaal River.

Conservation implications

Largemouth yellowfish can serve as an appropriate indicator of the effect of these environmental variable changes as they exhibited complex behavioural responses to environmental changes in mainstream riverine habitats. The major threats to largemouth yellowfish in the Vaal River are associated with industrial/mining effluents, agricultural return flow, unfiltered effluent from municipal waste water treatment plants and solid waste in the storm water return flow (Impson et al. 2008) hampering the water quality (Wepener et al. 2011). Our study indicated that water clarity, emergent and overhanging marginal vegetation, rapid biotope, nutrient load and salinity clearly have a pervasive influence on fish movement, facilitating efforts to predict how fishes respond to environmental change. Influence of such factors could affect persistence and colonisation rates of such sensitive fish species in the long-term. Based on this, movement behaviour of this species could be important for management and conservation actions in this riverine system. The relationship between ecological factors and fish movement can be considered of relevance for future experimental and field research. These components are crucial for subsequent water quality monitoring and predicting changes in fish populations as a direct result of anthropogenic disturbances (Merciai et al. 2014). Consequence of pollutants discharged in the aquatic environment is likely to accumulate and cause potential risk not only to the fish species but also to piscivorous bird and mammal species including humans. Hence, it is essential to minimise the major sources of phosphorus from runoff from agricultural fertilizers, manure, and organic sewage wastes and industrial effluent into a river (Mallin et al. 1993; Anderson et al. 2002; Nhapi and Tirivarombo 2004).

Further studies should focus on the relationship between largemouth yellowfish feeding and their migratory behaviour in relation to dam and weir construction, characterise and evaluate spawning habitats and conditions, drought/flood refuge and emergent and overhanging marginal/aquatic vegetation, seasonal movements w.r.t different life histories of the study species, may have important implications for colonization and persistence of river fish populations (Matthews 1998; Albanese et al. 2004). Therefore, our study indicated freshwater fish species like the largemouth yellowfish can act as sensitive ecological indicators and illustrate some of the present habitat degradation pressures on freshwater ecosystems needing urgent attention.

Acknowledgements The study was co-funded by the Water Resource Commission (ZA), FlyCastaway Pty. Ltd., and the National Research Foundation (ZA). We acknowledge the contributions made by the Hoffman family from Wag 'n Bietjie, K. Fourie from the Elgro River Lodge, and Rocky Ridge in Parys for logistic support. L. Cronje, F. Jacobs, H. Venter, R. Wyma and A. Husted assisted in the collection of behavioural data in the study. We thank the College of Agriculture, Engineering and Science, University of KwaZulu-Natal and National Research Foundation (ZA) for the financial support of TR under the Post-doctoral Research Programme to write this manuscript, and Science and Engineering Research Board, a statutory body of the Department of Science & Technology, Government of India under Ramanujan Fellowship scheme while revising the manuscript. We thank R. Kalle for valuable editorial inputs on the draft version, and the reviewers for their constructive comments..

Author's contributions TR, GCO and CTD conceptualised the paper. GCO conducted the field work. TR analysed the data. TR wrote the manuscript; GCO and CTD provided editorial advice.

Compliance with ethical standards Our research and animal tagging process was approved by the North West Ethics Committee (NWU-00095-12-A4).

Conflict of interest The authors declare that they have no conflict of interest.

References

Akbarimehr M, Hosseini SA, Shariati F, Hodjati SM (2016) Impact of season and road on stream crossings and river water quality in Darabkola, Hyrcanian forest. Water Resour 43:369–376

Aksnes DL, Utne ACW (1997) A revised model of visual range in fish. Sarsia 82:137–147

Albanese B, Angermeier PL, Dorai-Raj S (2004) Ecological correlates of fish movement in a network of Virginia streams. Can J Fish Aquat Sci 61:857–869

Anderson DM, Glibert PM, Burkholder JM (2002) Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. Estuaries 25:704–726

Aparicio E, Sostoa DA (1999) Pattern of movements of adult *Barbus haasi* in a small Mediterranean stream. J Fish Biol 55:1086–1095

Barton BA (2002) Stress in fishes: a diversity of responses with particular reference to changes in circulating corticosteroids. Integr Comp Biol 42:517–525

Bartoń K (2013) MuMIn: multi-model inference, R package version 1.9.13. http://CRAN.R-project.org/package=MuMIn. Accessed 6 October 2014

Bates D, Maechler M, Bolker B, Walker S (2014) lme4: linear mixed-effects models using Eigen and S4. R package version 1.1–7. Retrieved July 19, 2014, from http://cran.r-project.org/package=lme4

Bertasso A (2004) Ecological parameters of selective helminth species in *Labeobarbus aeneus* and *Labeobarbus kimberleyensis* in the Vaal Dam, and an evaluation of their influence on indicators of environmental health. M.Sc. Thesis, Rand Afrikaans University, Johannesburg, South Africa. Pp 96

Bervoets L, Blust R (2003) Metal concentrations in water, sediment and gudgeon (*Gobio gobio*) from a pollution gradient: relationship with fish condition factor. Environ Poll 126:9–19

Boss SM, Richardson JS (2002) Effects of food and cover on the growth, survival, and movement of cutthroat trout (*Oncorhynchus clarki*) in coastal streams. Can J Fish Aquat Sci 59:1044–1053

Bovee KD (1986) Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology (No. FWS/OBS-86/7). USDI Fish and Wildlife Service

Braun E, Rogers KH (1987) The Vaal River catchment: problems and research needs. South African national scientific programmes report No.143. Pretoria

Bridger CJ, Booth RK (2003) The effects of biotelemetry transmitter presence and attachment procedures on fish physiology and behavior. Rev Fish Sci 11:13–34

Brind'Amour A, Lobry J (2009) Assessment of the ecological status of coastal areas and estuaries in France, using multiple fish-based indicators: a comparative analysis on the Vilaine estuary. Aquat Living Resour 22:559–572

Burnham KP, Anderson DR (1998) Introduction. In model selection and inference. Springer, New York, p 355

Burnham KP, Anderson DR (2002) Model selection and multimodel inference: APractical information-theoretic approach. Springer, USA, p 488

Calcagno V, de Mazancourt C (2010) Glmulti: an R package for easy automated model selection with (generalized) linear models. J Stat Soft 34:1–29

Chapman D (1996) Water quality assessments - a guide to use of biota, Sediments and Water in Environmental Monitoring. Published on behalf of UNESCO/WHO/UNEP. University Press, Cambridge. Pp 651

Collen B, Whitton F, Dyer EE, Baillie JE, Cumberlidge N, Darwall WR, Pollock C, Richman NI, Soulsby AM, Böhm M (2014) Global patterns of freshwater species diversity, threat and endemism. Glob Ecol Biogeogr 23:40–51

Conley DJ, Schelske CL, Stoermer EF (1993) Modification of the biogeochemical cycle of silica with eutrophication. Mar Ecol Prog Ser 101:179–192

Cooch E, White G (2005) Program mark: a gentle introduction. http://www.phidot.org/software/mark/docs/book (accessed 05.09.12)

Cooke SJ, Cowx IG (2004) The role of recreational fishing in global fish crises. Bioscience 54:857–859

Cooke SJ, Graeb BDS, Suski CD, Ostrand KG (2003) Effects of suture material on incision healing, growth and survival of juvenile largemouth bass implanted with miniature radio transmitters: case study of a novice and experienced fish surgeon. J Fish Biol 62:1366–1380

Cooke SJ, Paukert C, Hogan Z (2012) Endangered river fish: factors hindering conservation and restoration. Endan Spec Res 17:179–191

Dallas HF, Day JA (2004) The effect of water quality variables on aquatic ecosystems: a review. Water Research Commission, Pretoria

De Robertis A, Ryer CH, Veloza A, Brodeur RD (2003) Differential effects of turbidity on prey consumption of piscivorous and planktivorous fish. Can J Fish Aquat Sci 60: 1517–1526

De Villiers P, Ellender B (2007) Status of the Orange-Vaal largemouth yellowfish, *Labeobarbus kimberleyensis* (Gilchrist & Thompson, 1913). Technical Report on the State of Yellowfishes in South Africa. WRC Report No. KV 212/08, Water Research Commission, Pretoria, South Africa

De Villiers P, Ellender B (2008) Status of the Orange-Vaal largemouth yellowfish, *Labeobarbus kimberleyensis* (Gilchrist & Thompson, 1913). In: Impson ND, Bills IR, Wolhuter L, Eds. Technical report on the state of yellowfishes in South Africa. Technical report no. KV 212/08. Water Research Commission, Pretoria

Department of Water Affairs (DWA) (2010) River health assessment on the Vaal River: downstream of the Rietspruit and Vaal River confluence to the Erina spa bridge and Vaal River crossing. DWA project WP9672. Carried out by Jeffares and Green (Pty) Ltd. and the University of Johannesburg on behalf of the Department of Water Affairs, Sasol and Rand Water, South Africa

Department of Water Affairs and Forestry (DWAF) (1996) South African water quality guidelines. Volume 7: aquatic ecosystems. In: ISBN 0-7988-5338-7. Department of Water Affairs, South Africa

Ellender BR, Weyl OLF, Winker H (2012) Age and growth and maturity of southern Africa's largest cyprinid fish, the largemouth yellowfish *Labeobarbus kimberleyensis*. J Fish Biol 81:1271–1284

Elliott M, Whitfield AK, Potter IC, Blaber SJ, Cyrus DP, Nordlie FG, Harrison TD (2007) The guild approach to categorizing estuarine fish assemblages: a global review. Fish Fish 8:241–268

Fausch KD, Torgersen CE, Baxter CV, Li HW (2002) Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes a continuous view of the river is needed to understand how processes interacting among scales set the context for stream fishes and their habitat. Bioscience 52:483–498

Fee EJ, Hecky RE, Kasian SEM, Cruikshank DR (1996) Effects of lake size, water clarity, and climatic variability on mixing depths in Canadian shield lakes. Limnol Oceanogr 41: 912–920

Figueiredo BR, Mormul RP, Thomaz SM (2015) Swimming and hiding regardless of the habitat: prey fish do not choose between a native and a non-native macrophyte species as a refuge. Hydrobiol 746:285–290

Geisler ME, Rennie MD, Gillis DM, Higgins SN (2016) A predictive model for water clarity following dreissenid invasion. Biolog Invas:1–18

Gerhardt A (2007) Aquatic behavioral ecotoxicology-prospects and limitations. Hum Ecol Risk Assess 13:481–491

Gilliam JF, Fraser DF (2001) Movement in corridors: enhancement by predation threat, disturbance, and habitat structure. Ecology 82:258–273

Gowan C (2007) Short-term cues used by foraging trout in a California stream. Environ Biol Fish 78:317–331

Gowan C, Fausch KD (2002) Why do foraging stream salmonids move during summer? In: Ecology, behaviour and conservation of the *charrs*, genus *Salvelinus*. Springer, Netherlands

Gowan C, Young MK, Fausch KD, Riley SC (1994) Restricted movement in resident stream salmonids: a paradigm lost? Can J Fish Aquat Sci 51:2626–2637

Graham LD, Wilcox LW (2000) Algae. Prentice-Hall: Upper Saddle River, N.J

Graham MH (2003) Confronting multicollinearity in ecological multiple regression. Ecology 84:2809–2815

Gregg WW, Rose FL (1985) Influences of aquatic macrophytes on invertebrate community structure, guild structure, and microdistribution in streams. Hydrobiol 128:45–56

Gregory RS, Levings CD (1996) The effects of turbidity and vegetation on the risk of juvenile salmonids, *Oncorhynchus* spp., to predation by adult cutthroat trout, O. clarkii. Environ Biol Fish 47:279–288

Gutiérrez-Cánovas C, Velasco J, Millán A (2009) Effects of dilution stress on the functioning of a saline Mediterranean stream. Hydrobiol 619:119–132

Habit E, Belk MC, Parra O (2007) Response of the riverine fish community to the construction and operation of a diversion hydropower plant in Central Chile. Aquatic Conserve Mar Fresh Ecosys 17:37–49

Harrison TD, Whitfield AK (2004) A multi-metric fish index to assess the environmental condition of estuaries. J Fish Biol 65:683–710

Harrison TD, Whitfield AK (2006) Temperature and salinity as primary determinants influencing the biogeography of fishes in South African estuaries. Estuar Coast Shelf Sci 66: 335–345

Harvey BC, Nakamoto RJ, White JL (1999) Influence of large woody debris and a bankfull flood on movement of adult resident coastal cutthroat trout (*Oncorhynchus clarki*) during fall and winter. Can J Fish Aquat Sci 56:2161–2166

Hellawell JM (1986) Biological indicators of freshwater pollution and environmental management. 1st ed. Pollution monitoring series. Mellanby, K., (Series Editor) Elsevier Applied Science Publishers, London. Pp 546

Herbert NA, Steffensen JF (2005) The response of Atlantic cod, Gadus morhua, to progressive hypoxia: fish swimming speed and physiological stress. Mar Biol 147:1403–1412

Hirschowitz PM, Birkhead AL, James CS (2007) Hydraulic modelling for ecological studies for South African rivers. WRC Report No. K5/105. Water Research Commission, Pretoria, South Africa

Impson D, Swartz E (2007) *Labeobarbus kimberleyensis*. The IUCN Red List of Threatened Species 2007: e.T63292A12638641. https://doi.org/10.2305/IUCN.UK.2007.RLTS.T63292A12638641.en. Downloaded on 17 August 2016

Impson ND, Bills IR, Wolhuter L (2008) Technical report on the state of Yellowfishes in South Africa 2007. WRC report KV212/08. Water Research Commission, Pretoria

King AJ, Ward KA, O'connor P, Green D, Tonkin Z, Mahoney J (2010) Adaptive management of an environmental watering event to enhance native fish spawning and recruitment. Fresh Biol 55:17–31

Kirk JTO, Akhurst EGJ (1984) Turbidity and suspensoids. Limnological criteria for management of water quality in the southern hemisphere. South African national scientific programmes report 93:32–63

Lucas MC, Johnstone AD, Priede IG (1993) Use of physiological telemetry as a method of estimating metabolism of fish in the natural environment. Transact Amer Fish Soc 122:822–833

Maitland PS (1995) The conservation of freshwater fish: past and present experience. Biol Conserv 72:259–270

Mallin MA, Paerl HW, Rudek J, Bates PW (1993) Regulation of estuarine primary production by watershed rainfall and river flow. Mar Ecol Prog Ser 93:199–203

Matthews WJ (1998) Patterns in freshwater fish ecology. Kluwer Academic Publishers, Norwell, Massachusetts, p 756

Mazumder A, Taylor WD (1994) Thermal structure of lakes varying in size and water clarity. Limnol Oceanogr 39: 968–976

McCarthy TS, Pretorius K (2009) Coal mining on the Highveld and its implications for future water quality in the Vaal River system. In: International Mine Water Conference (pp. 19–23). South Africa

McCarthy TS, Arnold V, Venter J, Ellery WN (2007) The collapse of Johannesburg's Klip River wetland. S Afr J Sci 103: 391–397

Merciai R, Guasch H, Kumar A, Sabater S, García-Berthou E (2014) Trace metal concentration and fish size: variation among fish species in a Mediterranean river. Ecotoxicol Environ Safety 107:154–161

Monette MY, McCormick SD (2008) Impacts of short-term acid and aluminum exposure on Atlantic salmon (*Salmo salar*) physiology: a direct comparison of parr and smolts. Aquatic Toxicol 86:216–226

Mulder PFS (1973) Aspects on the ecology of *Barbus Kimberleyensis* and *Barbus holubi* in the Vaal River. Zool Afr 8:1–14

Newcombe CP, MacDonald DD (1991) Effects of suspended sediments on aquatic ecosystems. N Am J Fish Manage 11: 72–82

Nhapi I, Tirivarombo S (2004) Sewage discharges and nutrient levels in Marimba River, Zimbabwe. Water SA 30:107–113

Nilsson C, Reidy CA, Dynesius M, Revenga C (2005) Fragmentation and flow regulation of the world's large river systems. Science 308:405–408

O'Brien G, De Villiers P (2011) Aspects of the biology and ecology of the orange-vaal largemouth and smallmouth yellowfish in the Vaal River. WRC Report TT 508/11. Water Research Commission, Pretoria

O'Brien G, Nel L, De Villers P, Jacobs F, Hoffman A (2011) Home ranges, habitat use, migrations and general behaviour. In: O'Brien G, De Villiers P, 2011. Aspects of the biology and ecology of the orange-vaal largemouth and smallmouth yellowfish in the Vaal River. WRC Report TT 508/11. Water Research Commission, Pretoria

O'Brien GC, Bulfin JB, Husted A, Smit NJ (2012a) Comparative behavioural assessment of an established and a new tigerfish *Hydrocynus vittatus* population in two man-made lakes in the Limpopo River catchment, southern Africa. Afr J Aquatic Sci 37:253–263

O'Brien GC, Bulfin JB, Husted A, Smit NJ (2012b) A Comparative behavioural assessment of an established and new tigerfish (*Hydrocynus vittatus*) population in two artificial impoundments in the Limpopo catchment, southern Africa. Afr J Aquatic Sci 37:253–263

O'Brien GC, Jacobs F, Cronje L, Wepener V, Smit NJ (2013a) Habitat preferences and movement of adult yellowfishes in the Vaal River, South Africa. S Afr J Sci 109:01–08, 1

O'Brien GC, Jacobs F, Burnette M, Krüger P, Botha IF, Cordier JA (2013b) Remote and manual radio telemetry methods to monitor and use fish behaviour in South Africa's inland waters. WRC Report 2111/1/13. Water Research Commission, Pretoria

Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, Galat DL (2005) Standards for ecologically successful river restoration. J Appl Ecol 42:208–217

Peretyatko A, Teissier S, Symoens JJ, Triest L (2007) Phytoplankton biomass and environmental factors over a gradient of clear to turbid peri-urban ponds. Aquatic Conserv Mar Fresh Ecosys 17:584–601

Petty JT, Grossman GD (2004) Restricted movement by mottled sculpin (Pisces: Cottidae) in a southern Appalachian stream. Fresh Biol 49:631–645

R Development Core Team (2014) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved April 10, 2014, from http://www.r-project.org/

Rahel FJ, Keleher CJ, Anderson JL (1996) Potential habitat loss and population fragmentation for cold water fish in the North Platte River drainage of the Rocky Mountains: response to climate warming. Limnol Oceanogr 41:1116–1123

Revenga C, Campbell I, Abell R, de Villiers P, Bryer M (2005) Prospects for monitoring freshwater ecosystems towards the 2010 targets. Philos Transac R Soc B: Biol Sci 360:397–413

Roberts JH, Angermeier PL (2007) Spatiotemporal variability of stream habitat and movement of three species of fish. Oecologia 151:417–430

Rogers KB, White GC (2007) Analysis of movement and habitat use from telemetry data. In: Brown M, Guy C (eds) Analysis and interpretation of freshwater fisheries data. American Fisheries Society Bethesda, MD

Schreck CB, Olla BL, Davis MW (1997) Behavioral responses to stress. In: Iwama GK, Pickering AD, Sumpter JP, Schreck CB (eds) Fish stress and health in aquaculture. Cambridge University Press, Cambridge

Schriever TA, Bogan MT, Boersma KS, Cañedo-Argüelles M, Kl J, Olden JD, Lytle DA (2015) Hydrology shapes taxonomic and functional structure of desert stream invertebrate communities. Freshwater Sci 34:399–409

Schultz R, Dibble E (2012) Effects of invasive macrophytes on freshwater fish and macroinvertebrate communities: the role of invasive plant traits. Hydrobiol 684:1–14

Schurmann H, Steffensen JF (1994) Spontaneous swimming activity of Atlantic cod *Gadus morhua* exposed to graded hypoxia at three temperatures. J Exp Biol 197:129–142

Skelton P, Bills R (2007) An introduction to African yellowfish. Technical report on the state of yellowfishes in South Africa, Water Research Commission, Pretoria, South Africa

Tallberg P (2000) Silicon and its impacts on phosphorus in eutrophic Freshwater Lakes. University of Helsinki, Helsinki, Academic Dissertation in Limnology

Uieda VS, Motta RL (2007) Trophic organization and food web structure of south eastern Brazilian streams: a review. Acta Limnol Brasil 19:15–30

Urbanek S (2010) rJava: low-level R to java interface. R package version 0.8–8. http://CRAN.R-project.org/package=rJava. Accessed 5 October 2014

Venables WN, Ripley BD (2002) Modern applied statistics with S, 4th edn. Springer, New York, p 498

Vidal-Abarca MR, Sánchez-Montoya MM, Guerrero C, Gómez R, Arce MI, García-García V, Suárez ML (2013) Effects of intermittent stream flow on macroinvertebrate community composition and biological traits in a naturally saline Mediterranean stream. J Arid Environ 99:28–40

Villiers SD, Thiart C (2007) The nutrient status of South African rivers: concentrations, trends and fluxes from the 1970s to 2005. S Afr J Sci 103:343–349

Vogel JL, Beauchamp DA (1999) Effects of light, prey size, and turbidity on reaction distances of lake trout (Salvelinus namaycush) to salmonid prey. Can J Fish Aquat Sci 56: 1293–1297

Walmsley RD, Bruwer CA (1980) Water transparency characteristics of south African impoundments. J Limnol Soc S Afr 6: 69–76

Wannamaker CM, Rice JA (2000) Effects of hypoxia on movements and behavior of selected estuarine organisms from the southeastern United States. J Exp Mar Biol Ecol 249:145–163

Wepener V, Van Dyk C, Bervoets L, O'Brien G, Covaci A, Cloete Y (2011) An assessment of the influence of multiple stressors on the Vaal River, South Africa. Phy Chem Earth Parts A/B/C 36:949–962

Zhang PD, Zhang XM, Li J, Gao TX (2009) Starvation resistance and metabolic response to food deprivation and recovery feeding in *Fenneropenaeus chinensis* juveniles. Aquacult Int 17:159–172

Zhang W, Cao ZD, Fu SJ (2012) The effects of dissolved oxygen levels on the metabolic interaction between digestion and locomotion in cyprinid fishes with different locomotive and digestive performances. J Comp Physiol B 182:641–650