Seasonal patterns in ichthyofaunal communities of fresh and estuarine wetlands in Vanua Levu, Fiji

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Executive summary

As a component of the Fiji Ecosystem Based management project, this study examined seasonal patterns of variation in the ichthyofaunal communities in seven river systems in Macuata and Kubulau districts, Vanua Levu, Fiji. The study was designed to determine the abundance, diversity and biomass of fishes within different reaches of the systems during the wet and dry seasons. Catchment characteristics clearly distinguish the districts in terms of potential impacts on ecological integrity. Macuata catchments, on average, are much larger (25789 *vs* 3306 ha), possess much less natural forest cover (49.6 *vs* 76 %), have greater density of roads (1.7 *vs* 0.51/km^2) and river crossings (1.4 *vs* 0/km^2), and are heavily invaded by exotic species *Oreochromis spp* and *Gambusia affinis*. Rainfall patterns are similar during the wet season for the districts but Kubulau has on average twice the rainfall during the dry season. 1616 individual fishes were collected or observed from 32 families, 19 genera and 87 species both seasons. 12% more species were seen during the wet season (68 *vs* 58), however the two districts show conflicting patterns with higher numbers of species in the wet in Kubulau District and higher numbers of species in the dry in Macuata District. Over half of species were observed in only one season (55%), 19 (21%) species only in the dry, 29 (33%) only in the wet. Proportions of life history patterns remain relatively consistent across both seasons although there are 6 % more estuarine migrant species (particularly mud dwelling species) and 1 % more amphidromous species in the wet while there is a 4% increase in freshwater straggler species in the dry mainly driven by additional pipefish species. It is clear that Kubulau, despite its smaller average catchment sizes is significantly (p = 0.035) more diverse than Macuata. Examination of community structure across reach and season suggest that position in river reach is a greater determinant of what species are in a community than season. A conflicting pattern between the districts with regard to seasonal influence on species richness, diversity, abundance and biomass of fishes if taken in conjunction with the water quality information, suggests the wet season is having a net positive effect on habitable space for fishes in Kubulau District and having a net negative effect in Macuata District. This result suggests degraded catchments are losing ecological resilience and natural responses to cycles of seasonal change. Comparison of mean abundance and biomass in Vanua Levu to the pristine rivers of Tetepare Island, Solomon Islands suggest that the rivers of Vanua Levu are already severely ecologically compromised and in most cases adequate biomass for food utilization is only energetically worthwhile in lower reaches.

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Introduction

Tropical high island ichthyofaunas are unique, with high densities of endemics (Abell et al 2008), and a high proportion of diadromy and facultative movement across marine and freshwater boundaries (McDowall 2007; Jenkins et al. 2009). These diadromous life history traits coupled with particular morphological characteristics (e.g. anguilliform shape, pelvic suction disc, dorso-lateral flattening) are considered important for population persistence within the context of temporal impermanence of waterways (Ryan 1991; Keith 2003; Jenkins et al. 2009) that characteristize tropical, oceanic high islands. This impermanence is an interaction of geology, with constant formation and disappearance of land at subduction zones and hot spots (Heads 2006), and hydrology with strongly seasonal precipitation producing clear seasonal patterns of river discharge (Winemiller & Jepsen 1998; Terry 2005). Seasonal patterns of precipitation are recognized as a key variable influencing habitat quality and quantity and, in turn, population dynamics and species interactions. During wet seasons, physicochemical characteristics such as water temperature and conductivity tend to be lower, and water depth, velocities, and dissolved oxygen concentrations tend to be greater (Winemiller & Jepsen 1998). In addition, seasonal variation in the transport of nutrients, detritus, or food between habitats or larger landscape units, as well as animal movement between habitat patches or ecosystems, can greatly influence productivity, material cycling, and predator–prey interactions (Polis et al. 1997; Werner & Gilliam 1984).

This seasonal variation also significantly affects the availability and magnitude of ecosystem services such as fisheries and potable water. In a fisheries example, 30% of Queensland's total fish catch and up to 80% of the barramundi catch variation for specific regions can be explained by rainfall alone often with a lagged response to rainfall events (Meynecke et al. 2006). In an oceanic island example, seasonal pulses of freshwater into nearshore marine and estuarine environments are thought to be important seasonal cues for upstream migration of amphidromous species (Delacroix & Champeau 1992; Keith 2003), the most abundant and diverse components of Indo-Pacific freshwater fish communities. These mass migrations of juveniles not only support locally important, traditional fisheries (Bell 1999; Berrebi et al. 2005; McDowall 1984), they also likely provide important seasonal input to local food webs (Jenkins et. al 2009). Strong seasonality in river flow regimes has major influences not only on the structure and function of aquatic ecosystems but also impacts directly on the food and water availability of adjacent human populations and rates of water borne diseases such as dengue and other diarrhoeal illnesses (Singh et. al. 2001). Developing a clearer understanding of the structure and function of Pacific high island ichthyofaunal communities and their responses to seasonal changes in hydrological characters is critical to implementing holistic, ecosystem-scale management across terrestrial, freshwater and marine systems.

As a component of the Fiji Ecosystem Based management project, this study examined seasonal variation in the structure of ichthyofaunal communities in seven river systems in Vanua Levu, Fiji across two focal regions of Kubulau District and Macuata Province. This information is designed to inform the broader fields of high island, tropical ecosystem based management, as well as provide additional guidance to the many decision making stakeholders along the watersheds of Vanua Levu for future aquatic and cross-habitat management.

Materials and Methods

Study site

Surveys of fish species richness and abundance took place in rivers and streams of Kubulau District and Macuata Province of Vanua Levu, Fiji's second largest island. The climate, geology and sampling methodology are described in detail below.

Climate & geology

Fiji has a tropical climate given the latitude in the south west Pacific and the influence of the warm southern equatorial ocean current. The southeast sides of the main islands, including our Kubulau district study sites, face the predominant trade winds and therefore receive more precipitation than the northwest, which is rain-shadowed by interior highlands (Figure 1). The climate is seasonal with a wet season from November to April, when tropical cyclones often occur and a dry season from May to October. During the dry season there is an uneven distribution of rain days; rainfall seasonality is more pronounced for the leeward northwest of the high islands (e.g. our Macuata district study sites), which receive only 20% of the annual total in the dry months compared to 33% to the windward side (Terry 2005). Specifically examining rainfall patterns in our two study districts of Macuata and Kubulau (Table 1) reveals the normalized figures (from 1971 – 2000) to be a mean of 293.8 mm/month in Macuata in the wet season versus a mean of 79.7 mm/month in the dry season with a mean of 251.5 mm/month in Kubulau in the wet season versus a mean of 138.6 mm/month in the dry. In essence, Kubulau district receives around twice as much rainfall during the dry months as Macuata district.

In the Pacific region there are also strong ENSO controls on stream behaviour. For example, during El Nino induced droughts, rivers in the rain-shadowed northwest of Fiji's high islands, particularly Macuata province, experience critically low base flows. The Southern Oscillation Index (SOI) is the measure of the strength of ENSO activities and shows good correspondence with both tropical cyclone flood magnitude and critically low stream discharges after a 2 month time lag (Terry et al 2001). High magnitude rainfalls normally produce big flows in Fiji's rivers and large floods over riverbanks are a frequent problem (Kostaschuk *et al* 2001), because the upper sections of rivers have a rugged volcanic topography causing a high degree of hydrological shortcuts (Terry 2005). The coastal areas of northern Vanua Levu (e.g. Macuata) are particularly vulnerable to flooding because of the high number of embayments, a geological configuration that increases the potential of storm surge inundation combining with river floods (Terry & Raj 1999).

Vanua Levu geology is made up of volcanic rock types occurring mainly as lava flows, breccias and conglomerates. A chain of volcanic mountains aligned in a southwest to northeast orientation form a central highland spine and give the mountainous profile. Most river networks drain northwest or southeast and are separated by narrow, steep valleys frequently approaching 30^{o} or more. Upper river channels are often steep and boulder strewn, lower watershed areas are commonly hilly terrain with flat alluvial terraces and flood plains in valley bottoms (Terry 2005).

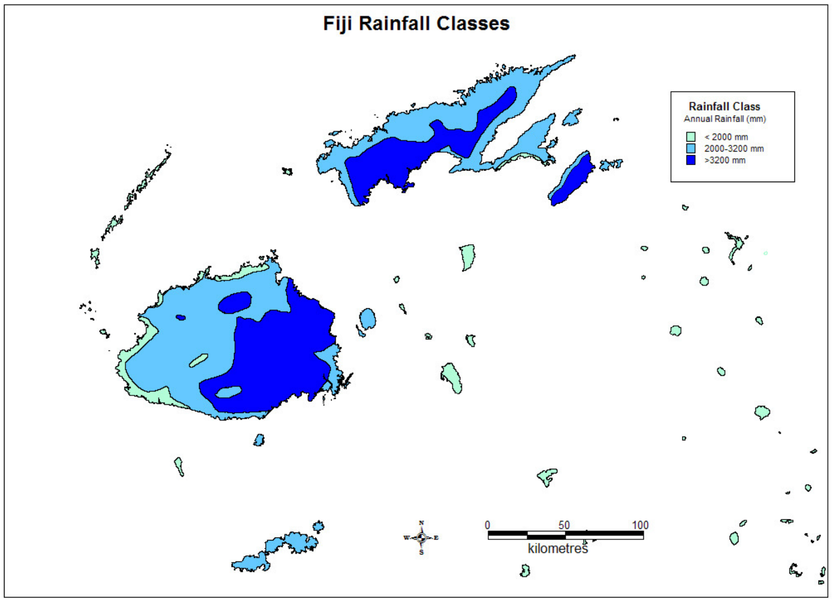


Figure 1. Mean annual rainfall patterns across the Fijian archipelago.
Figure from Atherton et al. 2005.

Table 1. Revised normals (1971 – 2000) for climate monitoring stations closest to Kubulau (Savusavu Airfield) and Macuata (Labasa Airfield) study areas reporting: mean daily maximum temperature (˚C); mean daily minimum temperature (˚C); mean daily temperature (˚C); total rainfall (mm); total sunshine (hr); and relative humidity (RH ; %).Source: Fiji Meteorological Service.

Station Number	Station Name		Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec	YEAR
V69435	Labasa Airfield	Max	31.7	31.6	31.5	31.0	30.2	29.8	29.2	29.4	30.1	30.8	31.4	31.7	30.7
		Min	22.2	22.4	22.3	21.3	19.9	18.9	18.1	18.7	19.3	19.8	21.2	21.7	20.5
		Mean	27.0	27.0	26.9	26.2	25.1	24.4	23.7	24.1	24.7	25.3	26.3	26.8	25.6
		Rainfall	385.7	344.1	373.0	236.9	114.6	66.7	54.2	47.6	71.7	123.6	182.2	240.8	2241.0
		RH	77.9	81.8	82.8	82.0	80.7	81.4	79.0	75.4	71.5	69.2	70.7	73.5	77.2
V69831	Savusavu Airfield	Max	30.6	30.7	30.6	29.8	28.5	27.9	27.0	27.1	27.4	28.2	29.4	30.2	29.0
		Min	23.5	23.7	23.6	23.2	22.3	21.6	21.0	20.8	21.2	21.9	22.6	23.0	22.4
		Mean	27.1	27.2	27.1	26.6	25.5	24.7	24.0	24.0	24.3	25.1	26.1	26.6	25.7
		Rainfall	275.4	244.4	283.0	260.6	196.5	118.9	96.2	116.2	132.9	170.6	188.0	257.8	2340.0
		RH	79.3	80.8	81.9	82.2	81.0	81.1	79.8	79.5	78.7	77.7	78.2	78.1	79.9

Table. 2. Summary of several key catchment characteristics within the sampled areas across two study districts of Macuata and Kubulau (from Atherton et al. 2005 and Jenkins et al. 2009)

Catchment Name	District	Area (ha)	% forest cover	Relative erosion potential	Road density per km^2	River crossings per km^2	Invasive fishes present
Dreketi	Macuata	85053	57	Medium	1.95	1	YES
Labasa	Macuata	20728	61	High	2.51	2	YES
Qawa	Macuata	15205	54	High	1.96	2	YES
Tabia	Macuata	7651	47	Medium	1.82	2	YES
Nataqaga	Macuata	307	29	High	0.1	0	NO
Kilaka	Kubulau	2474	80	Medium	0.44	0	NO
Suetabu	Kubulau	4138	72	High	0.57	0	NO

Table 2 shows a number of key catchment characteristics that also clearly distinguish the districts in terms of potential impacts on the integrity of the water bodies. Macuata catchments are, on average, much larger (25789 *vs* 3306 ha), possess much less natural forest cover (49.6 *vs* 76 %), have much greater density of roads (1.7 *vs* 0.51/km^2) and river crossings (1.4 *vs* 0/km^2), and are heavily invaded by exotic species such as tilapia (*Oreochromis* spp) and mosquitofish (*Gambusia affinis*).

Sampling methodology

The field procedures described herein are adapted from those described in Parham (2005) and Fitzsimons et al. (2007) and refined from the field experiences of the author. These methods are designed to provide the most comprehensive documentation of fishes present in a variety of stream and river habitats in tropical oceanic island ecosystems while also providing an accurate snapshot of the habitable space. The methods and best practices for freshwater monitoring on tropical, high Pacific islands are described in A Guide to Best Practice for Freshwater and Marine Biological Monitoring for Ecosystem-Based Management (EBM-Fiji 2009). In our study for the Fiji Ecosystem Based Management (EBM) project we used fishes, particularly gobioid families Gobiidae & Eleotridae) as primary indicators of environmental quality as fishes: (1) are taxonomically most well studied and most observable inhabitants of these systems; (2) represent critical components of the food web from primary consumers (herbivores) to predators; and (3) have recognized value as food sources for inland communities.

Site selection and standardization

Our study was designed to determine the abundance, diversity and biomass of fishes within different reaches of the system during the wet and dry seasons. We surveyed a range of habitats from small creeks to large turbid rivers, torrential mountain streams, mangrove swamps and river mouths (Figure 2). Specific collecting/survey methods were selected depending on the habitat type and are discussed in the following sections. Rivers and streams were selected on the windward and leeward sides of the island and sampled once during the wet season and once during the dry. Each river or stream was divided into three sections coinciding with known distribution of adult animals. We designated these three sections as lower reach, middle reach and upper reaches. Lower reach sites generally occur from the river mouth to the first major obstacle to fish passage (ie. waterfall, culvert, weir). Estuaries, with a free connection to the open ocean and mixing of salt and freshwater, were included in the investigation of lower reach sites. A second lower site was usually conducted just beyond the tidal reach of salty water. Middle reach sections were in pure freshwater at a moderate to low incline with riffle, run and pool development. Typically two sections of middle reaches were sampled: one just above the first major obstacle and another sample was taken 100 - 200 meters further upstream. Upper reach sites are generally characterized by steep gradient headwater areas with waterfalls and plunge pools. Our approach was generally to sample once above the largest headwater waterfall and once below, although variation in length, grade and waterfall formation meant this was not always possible. As many techniques were used as possible at each site to gain the most comprehensive understanding of species presence or absence. Standardization of sampling included apparatus used, length of reach sampled, sampling time and number of surveyors. In general, 50 meter sections of streams and rivers were sampled with a combination of a single electro-fishing apparatus, several seine and hand nets by 4 – 6 surveyors, from the downstream section of the site working upstream and were sampled for approximately one hour per site. Statistical tests were performed with Statistica v. 7 software to assess differences in Shannon-Weaver diversity indices, abundance and biomass by district, reach and season. Differences in community structure were evaluated from presence/absence data in Primer v. 6 software.

Description of sampling sites

Upon selection of the sampling site we embarked on a systematic description of the site to provide a record of the habitat conditions and allow study of conditions suitable for fish habitation. Firstly, two digital photographs were taken facing upstream and then downstream of the sampling site. The site data sheet was filled out with field station number, water body name, date, start time, GPS point, collectors, weather condition and a rough site map was drawn. At each sampling site a GPS position and altitude were taken using a Garmin GPS *map* 76Cx. Water quality characteristics were taken before entering the water to minimize disturbance to natural water characteristics. Temperature, pH, conductivity, salinity and dissolved oxygen were taken using a hand-held YSI multi-meter. Turbidity was taken using a turbidity tube calibrated to Nepthalometric Turbidity Units. Flow rate was taken by floating a plastic lid over a marked ten meter section and timing with a stopwatch. Brief notes were also taken on riparian vegetation and in stream condition with particular emphasis on substrate type, flow type, in stream cover, aquatic vegetation, riparian vegetation, land use type and major disturbance type. Water body maximum width and depth were also taken using a waterproof fibreglass tape.

Sampling for fishes

As many collection techniques were used as possible at each site to gain the most comprehensive understanding of species presence or absence. The following apparatus and techniques were used:

Electro-fisher (Deka 3000, 600V, 10A; Smith-Root LR-25; 500V, 10A) a primary sampling tool in river and streams. Wearing rubber waders and never venturing deeper than 1.5 meters, the anode (on a meter long rod) was discharged while two people (also wearing rubber waders) held a medium -sized, 1 mm^2 mesh net across the stream several meters upstream from the anode. As the anode reached the net, it was raised and fauna within the net were placed in a water-filled plastic bucket. Care must be taken to not touch water with uninsulated skin while the electro-fisher is being discharged. Stunned fish were also captured by small hand nets in between pulses.

Gill net *(25m x 1.8m, 1 inch mesh)* were used in lower sites and deployed with the floaters along the top edge and the lead weights along the bottom. Gill nets are the most effective way to sample large rivers**.** Soak time was approximately one hour before the net was removed.

Large seine net (2 m x 7 m, 0.4 cm^2 mesh) This net was pulled in a rough circle, with the bottom edge down as close as possible to the substrate and forward of the top floating edge of the net. This technique was executed before anyone could set foot in the water body to minimize the number of fleeing fishes. This was generally used in minor tributaries and slow moving or still waters.

Medium pole seine net (1.2 m x 0.8 m, $1mm^2$ mesh) was used in a variety of ways. Firstly, it was held firmly downstream as people kick and dislodge rubble upstream. This is a useful method for collecting small, bottom dwelling fish. On vegetated banks the net was thrust under submerged vegetation and the vegetation was disturbed on the bank dislodging fishes into the net. Also, this net was used to “scoop” (bottom edge held forward, run along substrate for a few seconds then lifted) from any accessible shallow body of water. This net was particularly useful for narrow streams and the net most commonly used in conjunction with the electro-fisher.

Small hand nets (15cm x 10cm + 10 cm x 8 cm, $1mm^2$ mesh) These were used to “scoop” the underside of overhanging rocks and in small crevices in the smaller streams and also to collect fauna when in still water bodies. These were also often used in conjunction with the electrofisher in between pulses to collect stunned fishes.

Observations (mask and snorkel) This method was only used in clear streams where there was no possibility of bull sharks. It is effective for obtaining a very quick overview of the local fish population and relative abundance of species. The method essentially consists of making underwater observations with the use of mask and snorkel. In areas that were shallow enough and the water was clear enough, a mask and snorkel were used to observe the benthos and fauna that were not being caught by the nets. Notes were recorded on plastic slates or special waterproof paper.

Preservation of specimens

For our study, voucher specimens were collected, fixed in a 10% formalin solution and transferred to 70% ethanol solution after 1 - 2 weeks of fixation. Some specimens were stored directly in 80% ethanol for DNA analysis. Voucher specimens were deposited at the University of the South Pacific, Suva collections. As color loss is rapid, accurate preservation of color patterns was recorded by photography. Fresh specimens were placed in a portable aquarium with some local aquatic vegetation and benthos to enhance the photography.

Identification of fishes

In general, the fish fauna of oceanic Pacific islands is quite poorly known, particularly at the species level within the highly speciose gobioid fishes. Based on previous work by the first author and students in Fijian rivers and streams, we constructed a waterproof set of index cards called the Fiji Freshest Fishdex, with the known freshwater/estuarine fish fauna on one side and the name on the other. These were used for both field identification and training of field identification (available from Wetlands International – Oceania). We also commonly used the field guides of Allen (1991) and Keith et al. (2002) from Papua New Guinea and New Caledonia, respectively. Other useful identification sources are listed in references. Unidentifiable fishes were noted according to definable characteristics in the field, photographed and preserved. All fishes that were not clearly identifiable were taken back to the USP Marine lab and available keys from the literature were used to key out all specimens. Particularly difficult species were sent to museum specialists in those particular taxonomic groups for confirmation.

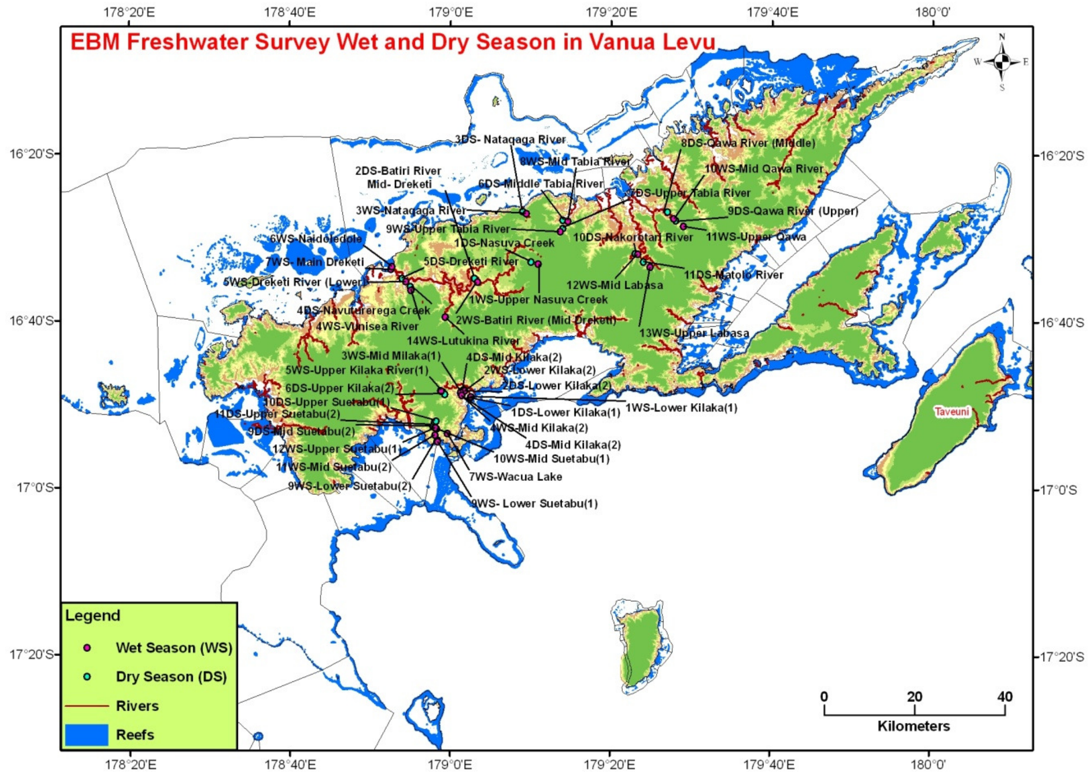


Figure 2. Map of Vanua Levu showing location of sampling sites. See Appendix 5 for a gazetteer of exact GPS locations.

Results and Discussion

Species richness

Species richness examines the absolute numbers of individual species observed. 1616 individual fishes were collected or observed from 32 families, 19 genera and 87 species (see Appendix 1) over both seasons. This is a little over half (52%) of the species of freshwater and estuarine fishes recorded from Fijian rivers (Jenkins, 2009). Overall, 12% more species were seen during the wet season (68 *vs* 58), however the two districts show conflicting patterns with higher numbers of species in the wet in Kubulau District and higher numbers of species in the dry in Macuata District (Figure 3). This conflicting pattern is also repeated for abundance of fishes (Figure 13) and possible explanations are discussed below.

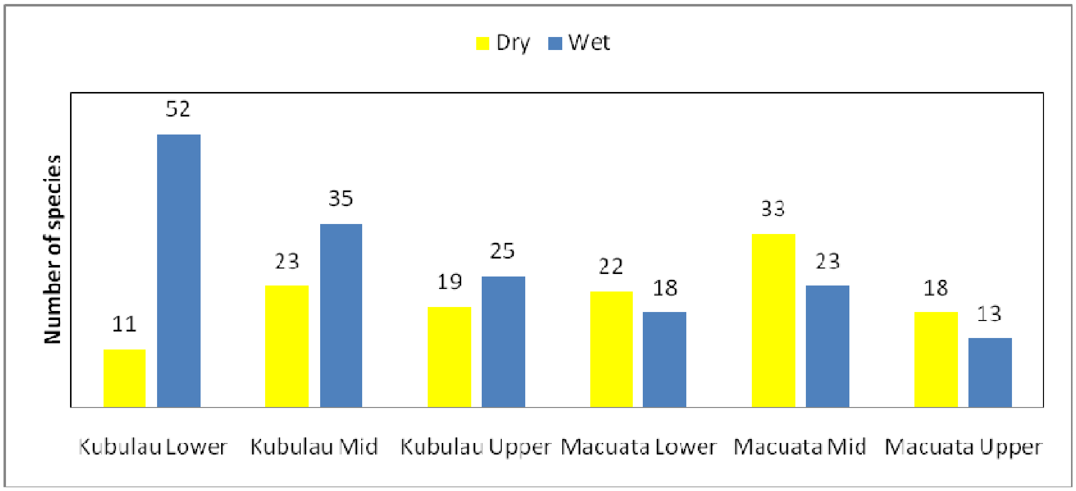


Figure 3. Numbers of species observed by reach and province over wet (blue) and dry (yellow) seasons.

Seasonal exclusivity

Over half (55%) of species were observed in only one season (55%): 19 (21%) species only in the dry, 29 (33%) only in the wet (Appendix 1). Of the exclusively dry season species 68% were only seen in the lower and mid reaches of the Dreketi system while 70% of the exclusively wet season species are found in Kubulau with only 6 species found in both districts in the wet. The species exclusive to the wet were generally larger contributing on average 191.54 g/species compared to 73.94 g/species in the dry.

The reasons for these seasonally exclusive observations are likely a combination of sampling variability and species level preferences for particular seasonally available habitats and water characteristics. For example, many of those species only seen during the dry season spend significant portions of their adult lives in marine and estuarine environments and are potentially capitalizing on the longer upward penetration of saline water during this season for feeding, breeding or to escape predation. Key species among this group are: the bull shark (*Carcharhinus leucus*); the snappers *Lutjanus johnii* and *L. monostigma*; tarpon (*Megalops cyprinoides*)*;* spaghetti eel (*Moringua macrocephala*); wolf herring (*Chirocentrus dorab*); and Hardenburg's anchovy (*Stolephorus insularis*). Also as the flow rate is much reduced during the dry season (Table 3) those species that are poor swimmers are more likely to be present in mid-water and more likely to be sampled then in the high flow wet season. Key examples among this group are the humpback cardinal (*Apogon lateralis*), the milkspotted puffer (*Chelonodon patoca*), and the silver moony (*Monodactylus argenteus*).

Those species that are only seen during the wet also appear to share some commonalities such as superior swimming ability in current, such as the: brassy trevally (*Caranx papuensis*); Pacific long-finned eel (*Anguilla megastoma*); and the pygmy barracuda (*Sphyraena obtusata).* Others in the wet, while also larger species, are likely taking advantage of the large amounts of allotchthonous matter being washed into the waterway as both a direct food source or as an attractant for smaller planktivorous prey items (eg. Indian mackerel *Rastrelliger kanagurta*; the mullets *Mugil cephalus* and *Liza sp*.; the snappers *Lujanus argentimaculatus* and *L. fulvus*; and the vermiculated spinefoot *Siganus vermiculatus*). Other wet season exclusive species prefer fresh muddy substrate as habitat which is in abundance in lower sites during the wet season, such as the mudskippers *Periopthalmus argentilineatus* and *P. kalolo*; scaleless wormgoby (*Caragobius urolepi);* longfin snake eel (*Pisodonophis cancrivorus*); and the unicolor snake moray (*Uropterygius concolor*). A key point in this result is that in order to completely understand species composition of island river systems sampling in both seasons is critical.

Diversity

While the concept of diversity is still debated among ecologists, in this study we are using species richness described above to give us the absolute number of species present while we are using among the most commonly used diversity measure, the Shannon-Weaver Index (H') to also take into account the abundance of individuals within each species. One particular caveat in using this measure is that the mathematical assumption is that all species present were observed which is highly unlikely given the difficulty in sampling many of the sites completely. However, we examine diversity by district and it is clearly evident that Kubulau, despite its smaller average catchment sizes is significantly (Mann Whitney U-test, p = 0.035) more diverse than Macuata (Figure 4). This is certainly a result of the greater ecological integrity of catchments in Kubulau with higher forest cover, less road development, river crossings and no invasive species (Table 2). Jenkins et al. (2009) clearly demonstrates the decline in numbers of native Fijian freshwater fish species in response to forest clearing and presence of introduced species. This result re-emphasizes that the rivers of Kubulau District have a greater ecological integrity than those in Macuata District.

We then examined overall diversity by reach which showed the expected trend of lowest diversity in upper reach sites with increasing diversity descending the catchment axis and highest diversity in the lower reach sites (Figure 5). While a Kruskal-Wallis ANOVA not show significant differences among reaches at the $p < 0.05$ level, the upper reach is almost significantly less diverse than the lower ($p = 0.065$). Despite lack of statistical significance, most likely related to low sample size and non-normal distributions, the trend is naturally evident and species attenuation with altitude and distance upstream has been extensively demonstrated (McDowall 1998; Joy & Death 2000; Rondon-Suarez & Petrere 2007). Generally only species within taxa with specialized swimming ability (e.g. anguilliform fish) and climbing ability (e.g. Gobiidae) will be able to reach most headwater sites (Eikaas & McIntosh 2006) and lower sites have much high numbers of estuarine and marine migrant species.

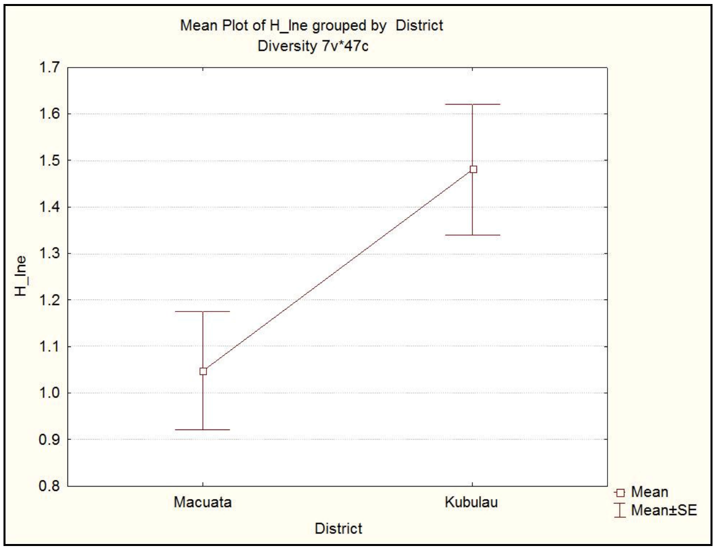


Figure 4. Mann-Whitney U test on Shannon-Weaver diversity index by district, summed across all reaches and seasons.

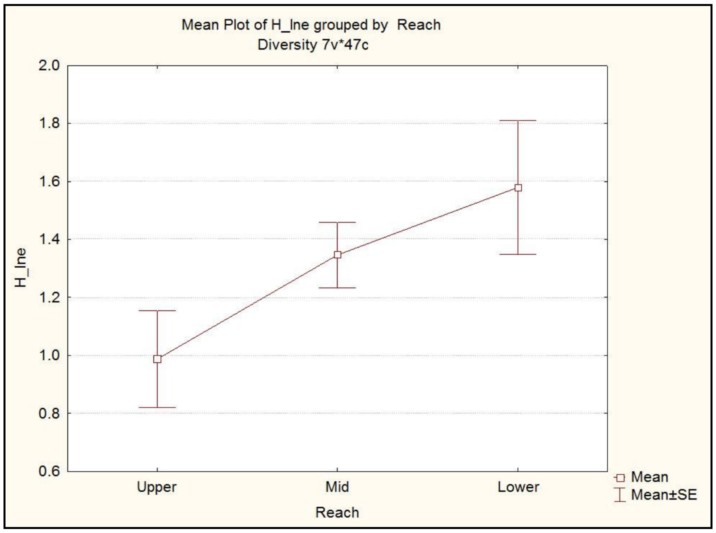
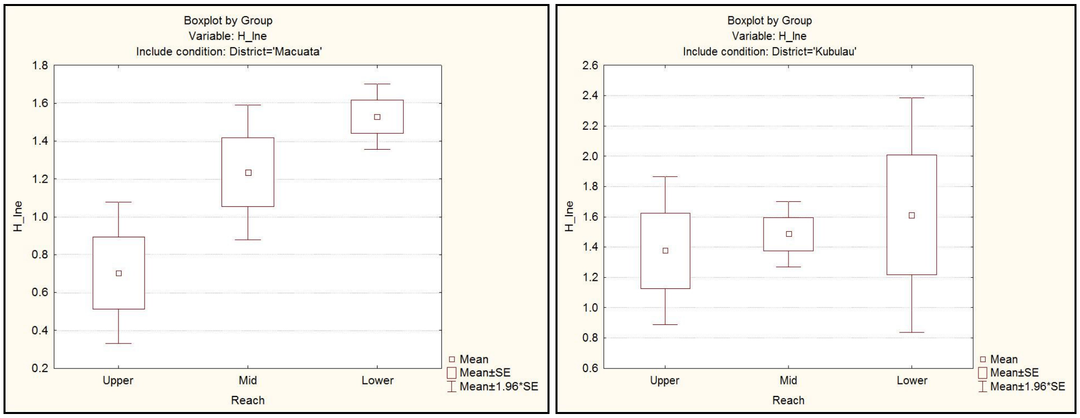


Figure 5. Kruskal-Wallis ANOVA by Ranks on Shannon-Weaver diversity versus river reach, summed across all seasons.

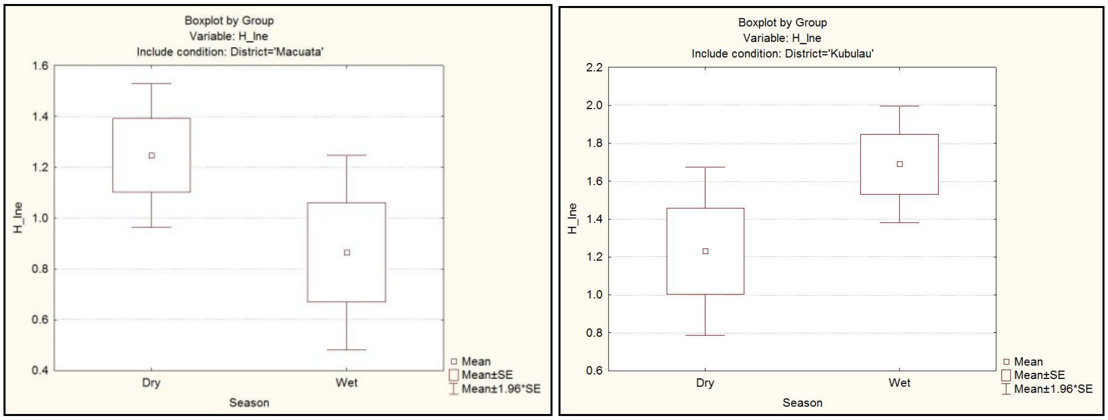
There is clear difference between districts in the level of species attenuation by reach if we examine the districts independently. The rivers of Macuata are generally larger with steeper upper reaches while those of Kubulau are smaller coastal catchments with more gradual incline and without many significant barriers such as large waterfalls. Macuata shows clearly significant decrease in diversity (Kruskal-Wallis ANOVA, p = 0.023) ascending from lower reaches to headwaters (Figure 6a) whereas Kubulau does not (Figure 6b) reflecting this topographical difference.



(a) Macuata (b) Kubulau

Figure 6. Kruskal-Wallis ANOVA by Ranks on Shannon-Weaver diversity summed across season versus river reach in (a) Macuata District and (b) Kubulau District

Examining diversity changes between seasons (Figure 7) again reveals opposing trends between the districts with Macuata showing greater diversity in the dry and Kubulau showing greater diversity in the wet. While neither test was significant the overall conflicting trend is repeated in species richness (Figure 3) and abundance (eg. Figure 12) giving weight to the ecological reality of the pattern.



(a) Macuata (b) Kubulau

Figure 7. Mann-Whitney U Test on Shannon-Weaver diversity summer across reach versus season for (a) Macuata District and (b) Kubulau District.

Community structure

To examine the structure of fish communities across Vanua Levu, we performed a cluster analysis based on a Bray-Curtis similarity matrix of species presence or absence pooled across reaches by district (Figure 8). The matrix reveals three major obvious groupings: (i) lower reach communities are distinct across both districts; (ii) mid reach Macuata is most similar to upper Kubulau but also groups with mid Kubulau; and (iii) upper Macuata communities are highly distinctive. Lower reach communities have a similarly distinctive combination of marine migrant, estuarine dependant and lower reach freshwater fauna. As the rivers of Kubulau are mostly low gradient, lack significant barriers and are quite short between upper and mid reaches, the Kubulau upper communities appear most similar to the mid reach communities of Macuata. Upper Macuata fish communities are highly distinctive primarily due to the dominance of the Vanua Levu endemic, *Redigobius sp*. This species is only found in the upper Dreketi and Lekutu catchments of Vanua Levu and is one of only two known fully freshwater resident fishes in Fiji.

To examine the effect of season on fish communities, we performed the test with sites pooled within reaches by season for each district (Figure 9). The cluster analysis reveals a relatively similar pattern. Lower reach communities are highly similar despite any changes in community due to season. Within lower reach communities, wet season communities were most similar while dry season Kubulau was most distinctive, in part due to the presence of juvenile bull shark (*Carcharhinus leucus*). Mid-reach communities group together by district regardless of season. Headwater communities of Kubulau are most similar regardless of season and headwater communities are again the most distinctive. Taken in combination, these results suggest that position in reach seems to be a more important determinant of community structure in these river systems than season.

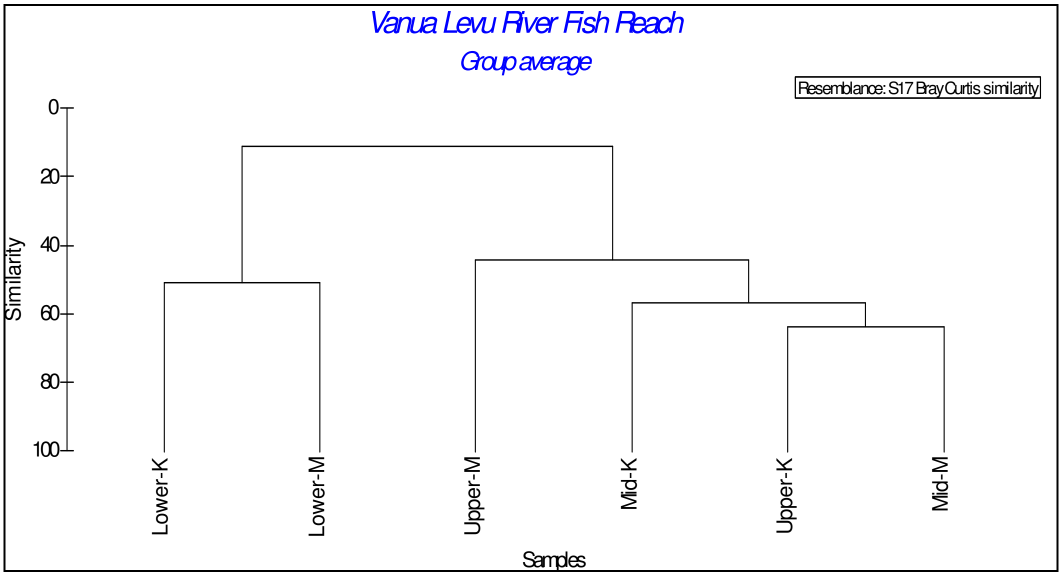


Figure 8. Cluster analysis (Group average) based on Bray-Curtis similarity matrix of presence/absence of species within reaches of each district (Kubulau – K; Macuata – M).

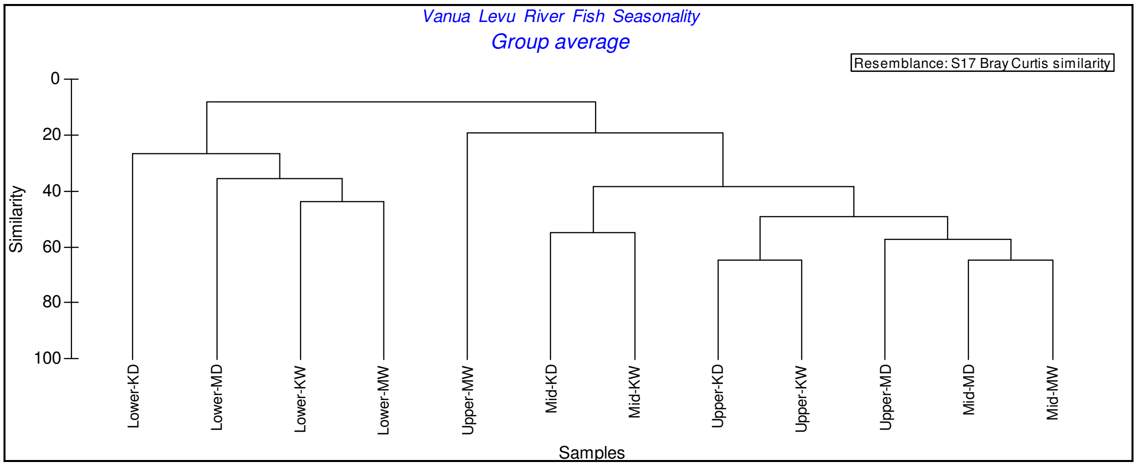


Figure 9. Cluster analysis (Group average) based on Bray-Curtis similarity matrix of presence/absence of species within reaches by season in each district (Kubulau – K; Macuta – M; Wet – W; Dry - D).

Endemic, endangered and rare species

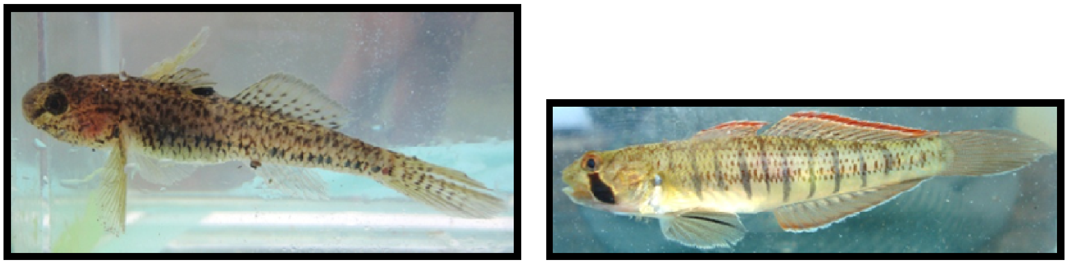
Six Fijian endemic fishes were collected from the study sites, *Redigobius leveri, Redigobius sp., Stiphodon* sp. 2, *Glossogobius sp.*, *Stenogobius sp.*, and *Hippichthys sp* (Figure 10). Of these, *Redigobius sp*. is the rarest and the most endangered being endemic to the upper Dreketi and Lekutu catchments. It is also one of only two known fully freshwater resident fishes in Fiji and perhaps only one of three in the oceanic island Pacific. It is likely critically endangered by catchment logging, invasive tilapia, and gravel extraction in particular. *Hippichthys sp.* is a newly discovered (2009) freshwater pipefish only known from the lower Dreketi river. *Redigobius leveri* is in all of the high islands of Fiji but is only found in clear flowing water in well forested areas. This is also one of only two fully freshwater resident fishes and the largest member of the genus worldwide. *Glossogobius sp.* and *Stenogobius sp.* are known Fiji endemics found on all the high islands and common throughout Fiji. The bull shark (*Carcharhinus leucus*(is listed as near threatened and the Otemobora mullet (*Liza melinoptera*) is listed as threatened on the IUCN red list. In addition, the mud dwelling gobies *Caragobius urolepis*, *Cristatogobius auromaculatus* are rarely collected and the photos presented here are among the only live color photos of these animals in existence.

Abundance and biomass

First cut examination of the importance of reach on abundance reveals the expected trend similar to that of diversity with increasing abundance descending from upper reach to lower reach sites. Tukey's post-hoc test of one way ANOVA showed significantly fewer fish ($p = 0.001$) in upper versus mid and lower reaches, which were not significantly different from each other (Figure 11a). Looking at the effect of reach on biomass reveals a similar pattern but with less difference between upper and mid sites and a more pronounced difference to lower reach sites. Tukey's post-hoc test showed significantly less biomass ($p = 0.027$) in upper than lower reaches, but mid reaches were not significantly different from either (Figure 11b). These results reaffirm the importance of reach in determining mean abundance and biomass while also emphasizing the significantly greater abundance and biomass in lower reach sites.

As seen in previous examinations of patterns of species richness and diversity, abundance of fishes also shows a similar opposing seasonal pattern between the two study districts, with higher abundance in Macuata in the dry season and higher abundance in Kubulau in the wet season (Figure 12a). A two way ANOVA with district and season as categorical predictors of abundance revealed only the interaction term (district + season) as significant ($p= 0.004$). The trend with biomass was less clear with no significant differences but stronger seasonal differences in Kubulau (Figure 12b).

Redigobius sp. (END) *Redigobius leveri* (END)



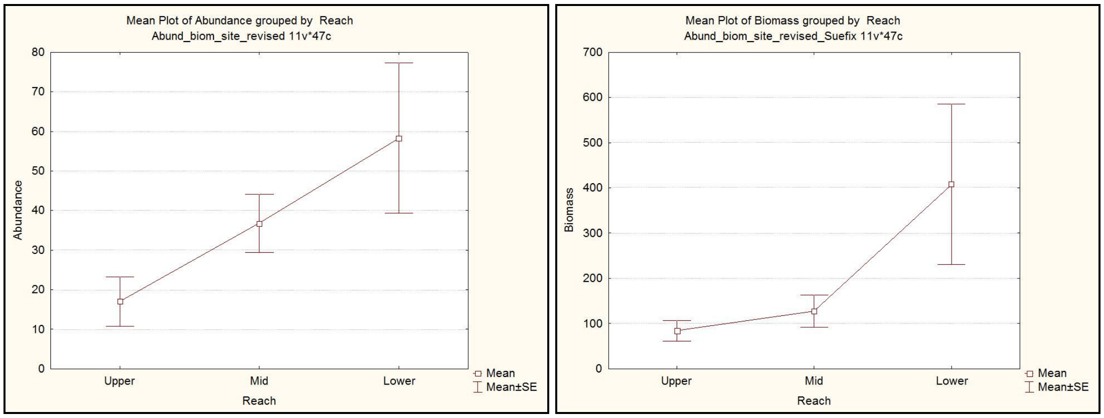
Glossogobius sp. (END) *Stenogobius sp.* (END)

Hippichthys sp. (END)

Caragobius urolepis

Cristatogobius auromaculatus *Stiphodon sp.2* (END)

Figure 10. Select endemic (END), endangered and rare species from Vanua Levu



(a) (b)

Figure 11. a) 1 way ANOVA of reach on abundance across both districts, b) 1 way ANOVA of reach on ln(x+1) biomass across both districts. Note graph b is plot of actual biomass in grams.

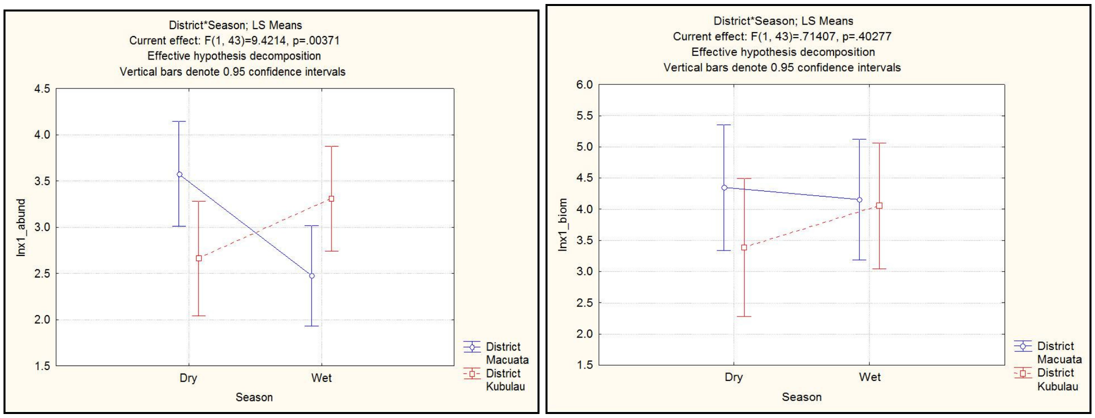
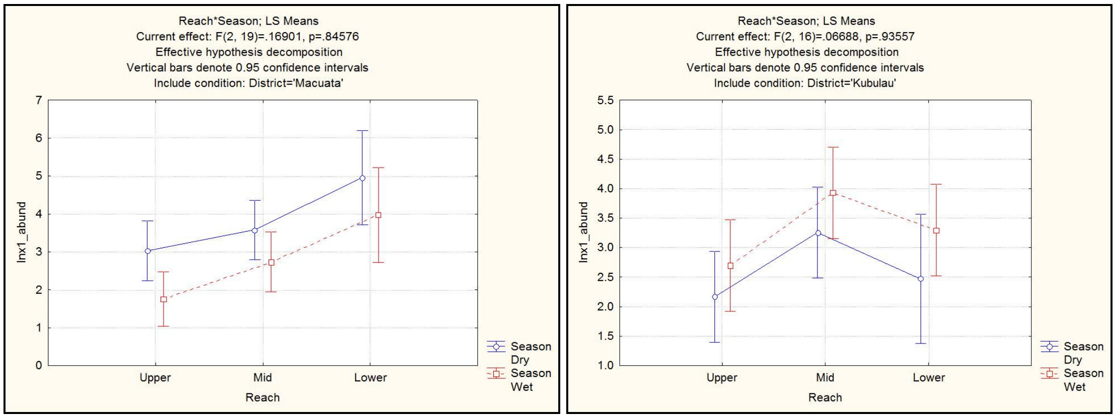


Figure 12. a) 2 way ANOVA with district and season as categorical predictors of transformed fish abundance, b) 2 way ANOVA with district and season as categorical predictors of transformed fish biomass.

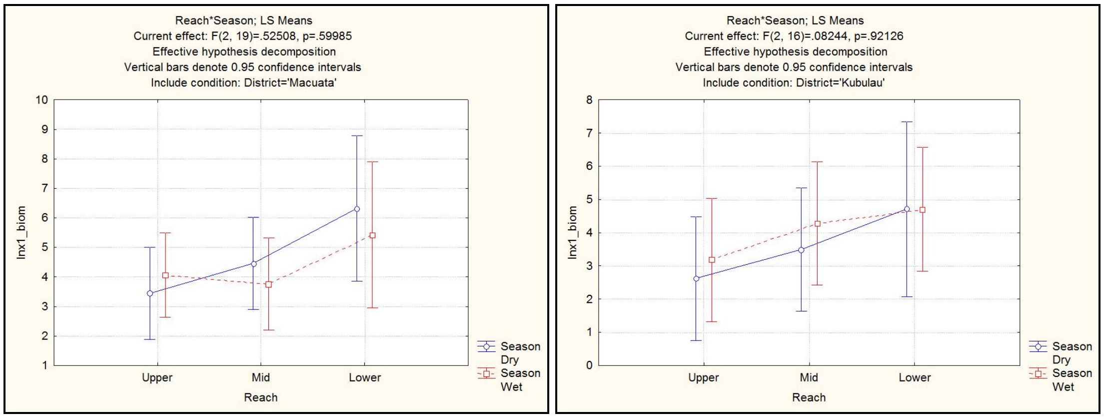
If we examine the districts independently for abundance by reach and season, we again see the same opposing trend being repeated (Figure 13 a, b). In Macuata, a two way ANOVA of reach and season on transformed abundance showed that both reach (p = 0.002) and season (p=0.012) were significant predictors (Figure 13a). Tukey's post-hoc test showed upper wet was significantly lower than mid dry, lower dry and lower wet sites. In Kubulau only the upper dry was significantly less than the mid wet, however the overall trend of greater average abundance in the wet is evident (Figure 13 b). While Macuata maintained the trend of increasing abundance from upper to lower reach sites, Kubulau had greater abundance on average in mid reach sites. Lower Macuata sites were generally deep and part of the large Dreketi river system with larger schools while lower Kubulau sites were shallow and commonly adjacent to reef flat with less larger schools of species than mid reach sites.



(a) (b)

Figure 13. a) 2 way ANOVA of reach and season on transformed fish abundance for Macuata, b) 2 way ANOVA of reach and season on transformed fish abundance for Kubulau.

Examination of seasonal effects on biomass by reach again shows the opposing trend between the two districts, although less clearly pronounced. A two way ANOVA of reach and season on transformed biomass showed no significant differences for Macuata or Kubulau (Figure 14a,b).

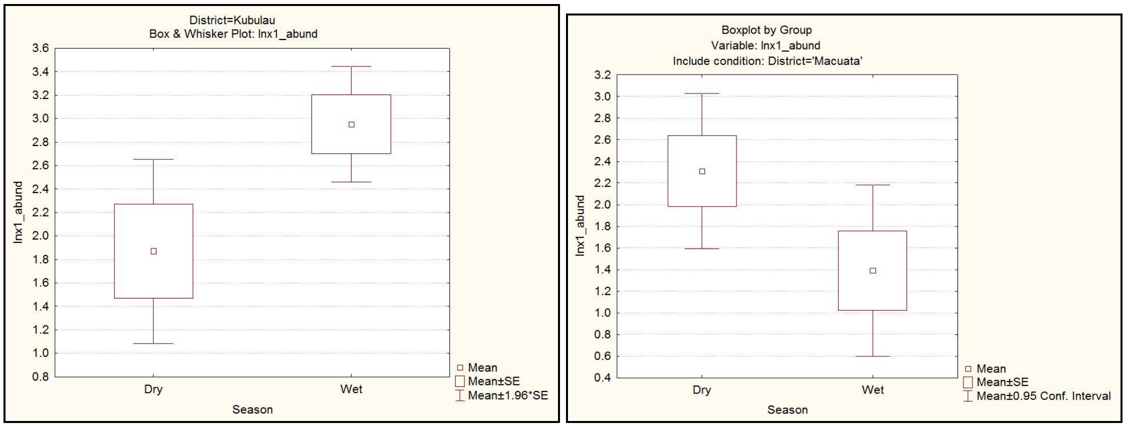


(a) (b)

Figure 14. a) 2 way ANOVA of reach and season on transformed biomass for Macuata, b) 2 way ANOVA of reach and season on transformed biomass for Kubulau.

Generally, the effects of season on abundance and biomass appear less important than the effects of reach and district. However, while not statistically significant, it does appear evident that season has a greater effect on abundance (Figure 13) than biomass (Figure 14).

The common thread throughout the various examinations of species richness, diversity, abundance and biomass is that the two districts are responding in predictably opposite ways to the season. Finally, we examine this phenomenon specifically looking at the abundance of gobioid fishes (Families Gobiidae and Eleotridae) as an indicator group and the most common inhabitants of Pacific island streams and rivers. Again, the pattern is predictably reversed for the two districts with a significantly higher abundance of gobioid fish in the wet in Kubulau (T-test, p = 0.028184) and a higher abundance (though statistically non-signifcant) in the dry in Macuata (Mann Whitney U-test, Figure 15).



(a) (b)

Figure 15. (a) T-test abundance of gobioids in Kubulau, b) Mann Whitney U test of abundance of gobioids in Macuata (several sites with zero abundance in dry season so not normally distributed).

The collective body of evidence presented in this report with regard to seasonal influence on species richness, diversity, abundance and biomass of fishes in conjunction with the water and habitat quality information presented below (Table 3) suggests that while the wet season is having a positive effect on habitable space for fishes in Kubulau District, it is having a negative effect in Macuata District. This result suggests that degraded catchments may be losing their ecological resilience and natural processes associated with cycles of seasonal change. The changes in habitat quality by district are discussed further with regard to water characteristics below.

Level of intactness

While we don’t have comparative seasonality data available for any intact tropical oceanic island, we do have dry season data only for Tetepare Island, Solomon Islands which is the largest uninhabited island in the Pacific (Jenkins & Boseto 2007). This can give us a rough feel for the degree of intactness of the Vanua Levu systems. If we look only at numerical abundance then on average Tetepare rivers yielded 65.6 fishes/ hr of sampling compared to 33.2 for the sampled Vanua Levu rivers. Looking at biomass, Tetepare rivers yielded on average 5.2 kg/ hr of sampling compared to 0.2 kg/hr in Vanua Levu. The highest biomass caught in any one site for Vanua Levu was 5.4 kg/ hr in the lower Dreketi *vs* 22.7kg /hr in the much smaller lower Raro river in Solomon Islands. These results suggest that the rivers of Vanua Levu are already severely ecologically compromised and in most cases adequate biomass for utilization for food is energetically only worthwhile in lower reaches. River restoration through riparian revegetation and freshwater protected areas may be able to restore some of the lost functionality of these systems (Humphries and Winemiller 2009).

Water quality characteristics

Table 3. Summary of seasonal mean values of site and water quality characteristics in two districts of Vanua Levu. Wet season values are in blue and dry season values are in yellow. Complete data set by season and site available in Appendix 2.

	Macuata		Kubulau		Both	
Flow rate (m/s)	0.707	0.386	0.918	0.364	0.787	0.374
Altitude (m)	59.5	57.5	41.6	43.6	50.5	50.5
Depth (m)	1.0	0.8	1.75	0.9	1.4	0.85
Width (m)	17.9	14.7	15	7.7	16.5	11.2
Temperature (˚C)	26.7	25.6	25.9	26.9	26.4	26.2
Salinity (ppt)	0.05	0	0.04	0.04	0.05	0.02
pH	7.26	7.63	6.94	6.75	7.01	7.23
DO (mg/L)	4.35	5.01	7.65	6.62	6.2	5.86
Conductivity (µS)	77.14	169.88	143.04	225.5	110.09	197.7
Turbidity (NTU)	14.4	<10	12.7	<10	13.5	<10

The general pattern of water quality characteristics of Vanua Levu rivers and streams over the different seasons reveals only partial consistency with those described by previous authors in tropical systems (Winemiller & Jepsen 1998; Terry 2005). As expected, current speed was over double in the wet, rivers were about 60 cm deeper and 5 m wider, dissolved oxygen (DO) was slightly higher and turbidity was higher. Temperature and conductivity did not show the expected pattern with wet season water temperature and conductivity expected to be lower during the wet. Looking at the provinces separately, reveals quite separate conflicting patterns which are acting to cancel each other out in the overall analysis. Flow rate, width and depth are increasing more in

Kubulau than Macuata, perhaps a reflection of the smaller average catchment size. While Kubulau displayed the expected lower mean temperature during the wet, Macuata water temperatures actually rose by a degree during the wet season. While Kubulau displayed the expected higher mean values of dissolved oxygen during the wet, again, Macuata values actually dropped during the wet. If we take these factors together, as well as the known terrestrial habitat differences and the higher turbidity values for Macuata, it is evident that the more degraded catchments are actually becoming less habitable in the wet compared to Kubulau which appears to becoming more habitable. High turbidity levels and reduction in shading along rivers due to deforestation in Macuata is likely decreasing dissolved oxygen levels and increasing temperatures.   Highly bisected waterways and removing riffles (rocky shallow areas) for logging roads and gravel extraction may also be decreasing the oxygenation of the water. An increase in algae through both fertiliser runoff and sewage contamination is likely also decreasing the available oxygen in the water. Dissolved oxygen values approaching 4 mg/L in the wet are only acceptable to a few highly tolerant organisms. In general, DO across both seasons averages 4.7 in Macuata *vs* 6.4 for Kubulau. In comparison, the fully forested and pristine rivers of Tetepare, Solomon Islands, yield a mean DO value of 8.2 mg/L in the dry season when DO values are at their expected lowest (Jenkins & Boseto 2007).

Life history considerations

97% of the fishes in Fijian streams and rivers must interact with the marine or estuarine environment at some point in their lives (Jenkins et al., 2009). Examination of the life histories of those fishes collected during this study reveals eight distinct life history patterns as present (Figure 16). Using the life history classification system of Elliot et al. (2007), Vanua Levu fishes are over half estuarine migrants and amphidromous , followed by over 20% facultative or obligate catadromous species and only 2% entirely freshwater residents. While this pattern remains quite consistent across both seasons, there are an additional 6 % of estuarine migrant species (particularly mud dwelling species) and 1 % amphidromous species in the wet while there is a 4% increase in freshwater straggler species in the dry mainly driven by additional pipefish species.

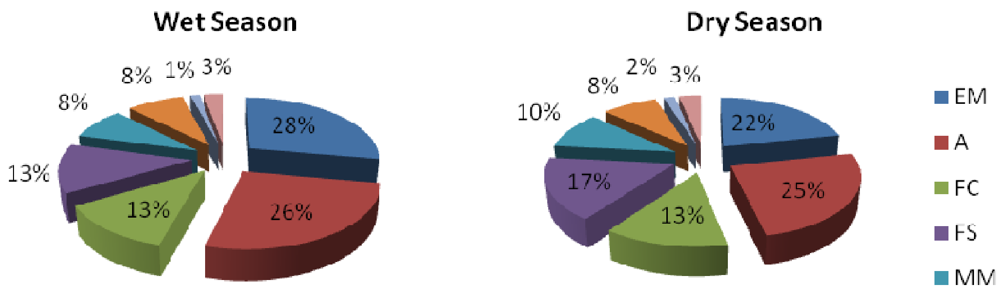


Figure 16. Life histories of Vanua Levu fishes present in wet and dry seasons. Life history classifications, after Elliot et al. (2007), include: freshwater resident (FR); freshwater straggler (FS); estuarine migrant (EM); marine migrant (MM); marine straggler (MW); amphidromy (A); obligate catadromy (COB); and facultative catadromy (FC).

In terms of abundance within these different life history categories few general trends are apparent with major differences between districts. In lower reaches, Macuata larger numbers of freshwater stragglers were apparent in the dry, particularly the glass perchlet (*Ambassis miops*) and also larger numbers of facultative catadromous species such as snappers and mullets. In Kubulau lower reaches there were many additional estuarine migrants in the wet spread across a number of species. In mid reaches many more freshwater stragglers were in the wet in Kubulau (particularly the gudgeon *Hypseleotris guentheri*) while in Macuata amphidromous species were more abundant, driven mainly by the gobiids, *Eleotris fusca* and *Sicyopterus lagocephalus.* In upper catchment areas, Kubulau saw greater abundance of amphidromous species in the wet while Macuata saw this trend reversed with more in the dry. In addition, the abundance of freshwater residents in Macuata was higher in the dry mainly due to high numbers of the mid-water schooling *Redigobius sp*.

Conservation and future research recommendations

- Upper Dreketi catchment is a globally unique ichthyofaunal community possessing the Vanua Levu endemic freshwater resident *Redigobius sp*. This area should be recognized as a global conservation priority for biodiversity and a critical headwater area for water recharge.
- The well forested and invasive free catchments of Bua, Kubulau are a national conservation priority as high connectivity corridors. Very few such catchments remain on any scale.

- Biodiversity surveys of freshwaters must incorporate sampling across seasons and in headwater, middle and lower reaches to gain a more complete understanding of the species richness.
- Seasonal restrictions for food fishes may yield best results around river mouths during the wet season in Kubulau and in the dry season in Macuata
- If limited by time, a rapid assessment of the ichthofaunal diversity of a system generally targeting lower reaches during wet season will yield greatest species numbers although fully freshwater residents will most likely be in mid and upper reach sites.
- Lower reach sites are a priority for food security, species richness and habitable space. Priority should be given to protection of lower reach areas in both districts.
- Upper reach sites are a priority for endemism and water security and should be afforded protection in both districts
- Future surveys for seasonality in fish communities should focus on one or two river systems and sample intensively over one month intervals over a whole year to gain a better overall understanding of fine scale community shifts. Also greater emphasis is needed in characterizing the riparian and in-stream habitat in relation to fish community structure.

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Appendix 1. Seasonal presence and absence of ichthyofauna by river reach across Macuata and Kubulau provinces, Vanua Levu, Fiji. Species are listed alphabetically. K = Kubulau; M = Macuata; L = lower; m=mid-reach; U=upper. Yellow shading indicates presence in the dry season and blue indicates presence in the wet season.

Family	Species	KL	KL	Km	Km	KU	KU	ML	ML	Mm	Mm	MU	MU
Ambassidae	*Ambassis miops*	🟨	🟦	🟨	🟦			🟨	🟦	🟨	🟦		
Anguillidae	*Anguilla marmorata*					🟨	🟦			🟨	🟦	🟨	🟦
Anguillidae	*Anguilla megastoma*												🟦
Apogonidae	*Apogon amboinensis*		🟦					🟨					
Apogonidae	*Apogon lateralis*			🟨									
Gobiidae	*Awauos guamensis*									🟨	🟦		🟦
Gobiidae	*Awauos ocellaris*				🟦	🟨				🟨		🟨	
Gobiidae	*Bathygobius coalitus*		🟦										
Eleotridae	*Bunaka gyrinoides*				🟦					🟨			🟦
Eleotridae	*Butis amboinensis*		🟦						🟦				
Eleotridae	*Butis butis*		🟦		🟦		🟦	🟨	🟦				
Gobiidae	*Caragobius urolepis*		🟦						🟦				
Carangidae	*Carangoides chrysophrys*							🟨	🟦				
Carangidae	*Caranx papuensis*								🟦				
Carangidae	*Caranx sexfasciatus*	🟨			🟦								
Carcharinidae	*Carcharhinus leucas*	🟨											
Diodontidae	*Chelonodon patoca*							🟨					
Chirocentridae	*Chirocentrus dorab*							🟨					
Gobiidae	*Cristatogobius aurimaculatus*		🟦					🟨					
Gobiidae	*Ctenogobiops aurocingulus*		🟦										
Diodontidae	*Diodon reticularis*	🟨	🟦										
Gobiidae	*Drombus halei*							🟨					
Eleotridae	*Eleotris fusca*			🟨	🟦	🟨	🟦			🟨	🟦	🟨	
Eleotridae	*Eleotris melanosoma*				🟦	🟨	🟦				🟦		
Apogonidae	*Foa fo*		🟦										
Poeciliidae	*Gambusia affinis*									🟨	🟦		
Leiognathidae	*Gazza minuta*		🟦										
Gerriedae	*Gerres sp.*	🟨											
Eleotridae	*Giurus hoedti*				🟦		🟦						
Gobiidae	*Glossogobius bicchirosus*								🟦				
Gobiidae	*Glossogobius sp (spot fin)*												🟦
Gobiidae	*Glossogobius sp.*		🟦			🟨	🟦	🟨		🟨	🟦	🟨	
Muraenidae	*Gymnothorax polyuranodon*			🟨	🟦	🟨							
Sygnathidae	*Hippichthys sp.*								🟦				

Belonidae	*Hyporhamphus dussumieri*		🟦										
Eleotridae	*Hypseleotris guentheri*			🟨	🟦	🟨	🟦			🟨	🟦	🟨	
Kuhliidae	*Kuhlia marginata*				🟦	🟨				🟨	🟦		
Kuhliidae	*Kuhlia munda*			🟨	🟦	🟨	🟦						
Kuhliidae	*Kuhlia rupestris*				🟦	🟨				🟨	🟦	🟨	
Ophichthiidae	*Lamnostoma kampeni*	🟨	🟦			🟨	🟦						
Leiognathidae	*Leiognathus equulus*	🟨	🟦					🟨	🟦				
Leiognathidae	*Leiognathus splendens*	🟨	🟦					🟨	🟦				
Mugilidae	*Liza melanoptera*		🟦					🟨					
Mugilidae	*Liza microlepis*							🟨					
Mugilidae	*Liza sp.*								🟦				
Mugilidae	*Liza subviridis*		🟦	🟨									
Lutjanidae	*Lutjanus argentimaculatus*		🟦										
Lutjanidae	*Lutjanus fulvus*		🟦										
Lutjanidae	*Lutjanus johnii*							🟨					
Lutjanidae	*Lutjanus monostigma*			🟨									
Lutjanidae	*Lutjanus russelli*		🟦					🟨					
Megalopidae	*Megalops cyprinoides*									🟨			
Sygnathidae	*Microphis brachyurus*			🟨	🟦						🟦		
Sygnathidae	*Microphis liaspis*									🟨			
Sygnathidae	*Microphis retzii*			🟨	🟦		🟦				🟦		
Monodactylidae	*Monodactylus argenteus*							🟨					
Moringuidae	*Moringua macrocephalus*											🟨	
Mugilidae	*Mugil cephalus*		🟦										
Gobiidae	*Mugilogobius notospilos*										🟦		
Eleotridae	*Ophiocara porocephala*		🟦	🟨	🟦		🟦		🟦				
Cichlidae	*Oreochromis mossambicus*						🟦			🟨	🟦	🟨	🟦
Gobiidae	*Oxyurichthys opthalmonema*		🟦					🟨					
Gobiidae	*Pandaka sp.*		🟦						🟦				
Gobiidae	*Periopthalmus argentilineatus*		🟦						🟦				
Gobiidae	*Periopthalmus kalolo*		🟦										
Ophichthidae	*Pisodonophis cancrivorous*		🟦										
Gobiidae	*Psammogobius biocellatus*		🟦	🟨					🟦				
Scombridae	*Rastrelliger kanagurta*								🟦				
Gobiidae	*Redigobius bikolanus*							🟨					
Gobiidae	*Redigobius leveri*					🟨	🟦				🟦		
Gobiidae	*Redigobius roemeri*		🟦	🟨									
Gobiidae	*Redigobius sp.1 (lekutu)*									🟨		🟨	🟦
Gobiidae	*Sicyopterus lagocephalus*			🟨		🟨				🟨	🟦	🟨	

Gobiidae	*Sicyopus zosterophorum*					🟨	🟦						
Siganidae	*Siganus vermiculatus*		🟦						🟦				
Sphyraenidae	*Sphyraena obtusata*		🟦										
Gobiidae	*Stenogobius sp.*			🟨	🟦		🟦				🟦		
Gobiidae	*Stiphodon rutilaureus*											🟨	
Gobiidae	*Stiphodon sp (lailai)*					🟨	🟦			🟨			
Engraulidae	*Stolephorus insularis*							🟨					
Terapontidae	*Terapon jarbua*		🟦					🟨					
Engraulidae	*Thryssa baelama*		🟦										
Mullidae	*Upeneus vittatus*	🟨											
Congridae	*Uroconger sp.*							🟨					
Muraenidae	*Uropterygius concolor*		🟦										
Gobiidae	*Yongeichthys nebulosus*		🟦										
Hemirhamphidae	*Zenarchopterus dispar*	🟨	🟦		🟦			🟨	🟦				

Appendix 2. Site and water quality characteristics at Vanua Levu sampling sites. Columns in blue are wet season values and columns in yellow are dry season values. Kilaka, Suetabu Rivers and Lake Wacua are in Kubulau, Bua Province, all of the other sites are in Macuata Province. Sites are numbered as: **1** – upper Kilaka 1; **2** - upper Kilaka 2; **3** – mid-Kilaka 1; **4** – mid-Kilaka 2; **5** - lower Kilaka 1; **6** - lower Kilaka 2; **7** -upper Suetabu 1; **8** - upper Suetabu 2; **9** - mid-Suetabu 1; **10** - mid Suetabu 2; **11 –** lower Suetabu 1**; 12 -** lower Suetabu 2; **13** - Wacua Lake; **14** – upper Dreketi 1 (Nasuva); **15** -mid Dreketi (Batiri); **16** – Nataqaga; **17** – upper Dreketi 2 (Vunisea); **18** – lower Dreketi 1; **19** - lower Dreketi 2; **20** – Naidoledole; **21** – mid Tabia; **22** – upper Tabia; **23** – mid Qawa; **24** – upper Qawa; **25** – mid Labasa; **26**-upper Labasa; **27** – Lutukina (upper Dreketi).

Site	Flow rate (m/s)		Altitude (m)		Temp (˚C)		Salinity (ppt)		pH		Dissolved Oxygen (mg/L)		Conductivity (µS)		Turbidity (NTUs)	
1	1.1	0.15	200	120	24.5	24.0	0	0	6.9	6.6	8.3	7.31	129.4	186.4	<10	**0**
2	1.2	0.51	>200	120	24.4	25.0	0	0	7.2	6.6	7.80	7.31	94.4	220.3	<10	**0**
3	1.1	0.6	50	20	26.0	24.5	0	0	6.9	6.7	7.13	6.46	99.8	160.6	14.4	**10**
4	0.9	0.6	50	20	26.4	25.0	0	0	6.8	6.7	7.13	6.26	83.2	170.4	15	**10**
5	0.7	0.5	0	0	27.5	27.6	0.2	0.1	6.8	6.8	7.51	6.22	199.9	223.4	15	**12**
6	0.5	0.09	0	0	26.4	28.4	0.1	0.1	7.2	6.8	9.96	6.71	786.0	256.7	15	**12**
7	1.1	0.04	60	60	24.0	27.6	0	0	7.1	6.6	7.40	6.67	80.0	190.4	<10	**0**
8	1.0	0.8	60	60	25.2	27.3	0	0	6.9	6.6	7.40	6.46	80.0	190.6	<10	**0**
9	1.1	0.4	30	40	25.3	28.5	0	0	6.9	6.9	7.50	6.44	80.0	290.3	<10	**10**
10	0.9	0.25	30	40	25.2	28.0	0	0	6.8	6.9	7.40	6.44	14.5	284.1	<10	**10**
11	0.5	0.18	0	0	27.6	29.0	0.1	0.2	6.9	7.1	8.40	6.54	97.2	307.6	20	**15**
12	n/a	0.25	0	n/a	26.7	n/a	0.1	n/a	n/a	n/a	8.47	n/a	58.9	n/a	20	**n/a**
13	n/a	n/a	20	n/a	28.6	n/a	0	0	4.2	n/a	5.15	n/a	56.3	n/a	20	**n/a**
14	0.86	0.61	123	123	25.1	22.9	0	0	7.0	7.1	4.00	7.50	70.6	102.5	20	**<10**
15	1.26	0.88	45	45	26.4	25.2	0	0	7.2	7.1	6.00	7.30	55	91.7	<10	**10**
16	0.59	0.52	n/a	n/a	25	25	0	0	8.7	8.6	6	7	n/a	97.5	<10	**<10**
17	1.35	0.15	68	68	26.2	24.8	0	0	8.4	9.5	7	5.7	65.5	128.64	20	**<10**
18	0.42	n/a	0	0	27.6	27.0	0.3	n/a	7.0	7.2	5.00	n/a	32.25	n/a	30	**n/a**
19	0.28	n/a	0	0	30.4	n/a	0.2	n/a	7.0	7.2	3.00	5.30	21.8	36.6	15	**10**
20	0.33	n/a	0	0	30.5	n/a	0.3	n/a	7.2	7.2	4.00	n/a	32.25	n/a	15	**n/a**
21	0.75	0.49	21	21	26.9	27.8	0	0	7.0	8.1	3.00	4.50	139.4	158.4	15	**0**
22	0.31	0.19	60	60	25.5	28.3	0	0	7.0	8.3	6.00	5.50	107.9	46.8	15	**<10**
23	0.78	0.08	30	30	25.7	26.9	0	0	7.0	7	4.00	1.00	105.8	326	<10	**<10**
24	0.48	0.63	80	80	26.8	25.0	0	0	7.5	7.5	4.00	5.00	101.4	455	<10	**<10**
25	0.65	0.7	24	24	28.1	24.2	0	0	6.7	6.5	4.00	1.50	105.3	329	<10	**<10**
26	0.74	0	45	45	25.3	25.0	0	0	7.0	8.0	4.00	n/a	82.4	96.6	<10	**10**
27	**1.10**	**0**	**120**	**120**	**25.2**	**n/a**	**0**	**n/a**	**7.0**	**n/a**	**8.00**	**n/a**	**83.3**	**n/a**	**<10**	**n/a**

Appendix 3. Species abundance by site, reach and season for Macuata district sites.

Sites numbers correspond to a site name for the water body followed by a three letter code corresponding to the province (M = Macuata, K = Kubulau), reach (U=upper, M =mid, L=lower) and season (D = dry, W = wet); Site 1 - Nasuva_MUD; 2 - Nasuva_MUW; 3 - Batiri_MMD; 4 - Batiri_MMW; 5 - Natagaqa_MMD; 6 - Natagaqa_MMW; 7 - Vunisea_MUD; 8 - Vunisea_MUW; 9 - Dreketi_MLD; 10 - Dreketi_MLD; 11 -Dreketi_MLW; 12 - Dreketi_MLW; 13 - Tabia_MMD; 14 - Tabia_MMW; 15 - Tabia_MUD; 16 - Tabia_MUW; 17 - Qawa_MMD; 18 - Qawa_MMW; 19 - Qawa_MUD; 20 - Qawa_MUW; 21 - Labasa_MMD; 22 - Labasa_MMW; 23 - Labasa_MUD; 24 - Labasa_MUW; 25 - Lutukina_MUW;

Genus species	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Anguilla marmorata					13	2	6	3					1	1	1	1			1	4	2	2		1	2
Anguilla megastoma																									1
Apogon amboinensis									1	9															
Caranx papuensis											1														
Carangoides chrysophrys									1			1													
Ambassis miops									114			3	3	2											
Chirocentrus dorab									1																
Oreochromis mossambicus		1	3										2				4	2			6	2	12	3	
Uroconger sp.										1															
Bunaka gyrinoides					3																1				1
Butis butis										4		1													
Butis amboinensis											1														
Eleotris fusca					36	2								1								2	1		
Eleotris melanosoma						1								1											
Hypseleotris guentheri													2	3			5		2		5				
Ophiocara porocephala											1														
Stolephorus insularis										3															
Awauos guamensis					1																1	1			1
Awauos ocellaris					1																1		2		
Caragobius urolepis												1													
Cristatogobius aurimaculatus									1	2															
Drombus halei										1															
Glossogobius bicchirosus											1														
Glossogobius sp (spot fin)		4																							
Glossogobius sp.									1				3	2	1				2				5		
Mugilogobius notospilos						1																			
Oxyurichthys opthalmonema									2																
Pandaka sp.												1													
Periopthalmus argentilineatus												3													
Psammogobius biocellatus											2														
Redigobius bikolanus										1															
Redigobius leveri				4																					
Redigobius sp.1 (lekutu)	124	21	1		1		3																		1
Sicyopus zosterophorum																									
Sicyopterus lagocephalus					13	6									4		1		1						
Stenogobius sp.														1											
Stiphodon rutilaureus															1										

Stiphodon sp (lailai)					5																				
Zenarchopterus dispar										35		22													
Kuhlia rupestris			1				6						5	9							3		1		
Kuhlia marginata					5									1							1				
Leiognathus equulus									16			24													
Leiognathus splendens									14		12														
Lutjanus johnii										7															
Lutjanus russelli										2															
Megalops cyprinoides													1												
Monodactylus argenteus									1																
Moringua macrocephalus							1																		
Liza melanoptera									1																
Liza microlepis									35																
Liza sp.											2														
Gambusia affinis			11														24	3							
Siganus vermiculatus											6														
Microphis brachyurus														7											
Microphis liaspis																					2				
Microphis retzii																		1							
Hippichthys sp.											22														
Terapon jarbua										4															
Chelonodon patoca										1															

Appendix 4. Species abundance by site, reach and season for Kubulau district sites. Sites numbers correspond to a site name for the water body followed by a three letter code corresponding to the province (M = Macuata, K = Kubulau), reach (U=upper, M =mid, L=lower) and season (D = dry, W = wet);26 - Kilaka_KLD; 27 - Kilaka_KLW; 28 - Kilaka_KLW; 29 - Kilaka_KMD; 30 - Kilaka_KMD; 31 - Kilaka_KMW; 32 - Kilaka_KMW; 33 - Kilaka_KUD; 34 - Kilaka_KUD; 35 - Kilaka_KUW; 36 - Kilaka_KUW; 37 - Suetabu_KLD; 38 - Suetabu_KLW; 39 - Suetabu_KLW; 40 - Suetabu_KMD; 41 - Suetabu_KMD; 42 - Suetabu_KMW; 43 - Suetabu_KMW; 44 - Suetabu_KUD; 45 - Suetabu_KUD; 46 - Suetabu_KUW; 47 - Suetabu_KUW

Genus species	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
Anguilla marmorata																				1	1	1
Apogon amboinensis													1	15								
Apogon lateralis																2						
Foa fo		1																				
Hyporhamphus dussumieri		1																				
Carcharhinus leucas	1																					
Caranx sexfasciatus							1					1										
Ambassis miops	3	2		1	2	7	13											3				
Diodon reticularis	1	2	2											2								
Bunaka gyrinoides							1															
Butis butis		1	2				1														1	1
Butis amboinensis														2								
Eleotris fusca				19		2	4			1					3		6		2		3	9
Eleotris melanosoma																	1			1		2
Giurus hoedti																	2				3	5
Hypseleotris guentheri				29	11	36	93								3		7	5	1	1	2	2
Ophiocara			3	2														2				1

porocephala																						
Thryssa baelama		1																				
Awauos ocellaris						2														1		
Bathygobius coalitus			2																			
Caragobius urolepis		1	1											14								
Cristatogobius aurimaculatus		4												8								
Ctenogobiops aurocingulus		2												2								
Glossogobius sp.													1	2					2	1		1
Oxyurichthys opthalmonema		12												2								
Pandaka sp.			4																			
Periopthalmus argentilineatus		6	1																			
Periopthalmus kalolo													2									
Psammogobius biocellatus		1	1													1						
Redigobius leveri									2		3											
Redigobius roemeri			1										1			4						
Sicyopus zosterophorum									7	4	3									1		
Sicyopterus lagocephalus								3	2						1							
Stenogobius sp.				12	7		1														2	
Stiphodon sp (lailai)									4	3	5											
Yongeichthys nebulosus		1																				
Gerres sp.												1										
Zenarchopterus dispar	2	1				2						5						2				
Kuhlia rupestris						1											2	1	1			
Kuhlia marginata																	2	2	1			
Kuhlia munda						5									1		2	16	2		3	3
Leiognathus equulus			1									1										
Leiognathus splendens	1	1																				
Gazza minuta		3																				
Lutjanus argentimaculatus		2																				
Lutjanus fulvus		1																				
Lutjanus monostigma																2						
Lutjanus russelli			1																			
Liza melanoptera														1								
Liza subviridis		1														2						
Mugil cephalus		1												1								
Upeneus vittatus												5										
Gymnothorax polyuranodon							3								2	4				1		
Uropterygius concolor														1								
Lamnostoma kampeni	1	2																		1		1
Pisodonophis cancrivorous		2																				
Siganus vermiculatus			1																			
Sphyraena obtusata		1												1								
Microphis brachyurus					1	1	4									3						
Microphis retzii				3		2	1								5		3	1				1
Terapon jarbua		1																				

Appendix 5. Gazetteer of Vanua Levu sampling sites given in decimal degrees over wet and dry seasons.

Sites	Season	Latitude (S)	Longitude (E)
Lower Kilaka (1)	DRY	16.820400	179.042000
Lower Kilaka (2)	DRY	16.805100	179.028000
Mid- Kilaka (1)	DRY	16.812500	179.021900
Mid-Kilaka (2)	DRY	16.808900	179.023510
Upper Kilaka (1)	DRY	16.809700	178.984000
Upper Kilaka (2)	DRY	16.814500	178.989000
Lower Suetabu	DRY	16.908100	178.973000
Mid-Suetabu(1)	DRY	16.883600	178.971000
Mid-Suetabu(2)	DRY	16.878600	178.964000
Upper Suetabu(1)	DRY	16.870600	178.967000
Upper Suetabu(2)	DRY	16.868200	178.970000
Lower Kilaka (1)	WET	16.820050	179.042980
Lower Kilaka (2)	WET	16.807110	179.030300
Mid- Kilaka (1)	WET	16.811100	179.021990
Mid-Kilaka (2)	WET	16.816310	179.023510
Upper Kilaka (1)	WET	16.807850	178.980410
Upper Kilaka (2)	WET	16.808280	178.980940
Wacua Lake	WET	16.893290	178.994260
Lower Suetabu(1)	WET	16.906340	178.973740
Lower Suetabu(2)	WET	16.909340	178.973300
Mid-Suetabu(1)	WET	16.883600	178.971300
Mid-Suetabu(2)	WET	16.895550	178.967790
Upper Suetabu(1)	WET	16.881270	178.967900
Upper Suetabu(2)	WET	16.881540	178.969600
Nasuva (Upper Dreketi)	DRY	16.550071	179.166931
Batiri (Mid Dreketi)	DRY	16.583406	179.050106
Natagaqa	DRY	16.450067	179.150123
Navuturerega (Upper Dreketi)	DRY	16.600122	178.916699
Lower Dreketi	DRY	16.583440	178.900133
Tabia (Middle)	DRY	16.466717	179.233512
Tabia (Upper)	DRY	16.483433	179.233384
Qawa (Middle)	DRY	16.450216	179.450226
Qawa (Upper)	DRY	16.466871	179.466933
Nakoroutari (Mid-Labasa)	DRY	16.533400	179.383453
Matolo (Upper Labasa)	DRY	16.550162	179.400245
Nasuva (Upper Dreketi)	WET	16.554330	179.182560
Batiri (Mid Dreketi)	WET	16.590480	179.056430
Nataqaga River	WET	16.453610	179.157010
Vunisea (Upper Dreketi)	WET	16.606750	178.918370
Dreketi (Lower)	WET	16.589710	178.907550
Naidoledole	WET	16.559970	178.878050
Main Dreketi	WET	16.565090	178.876330
Tabia (Mid)	WET	16.469430	179.243930
Upper Tabia	WET	16.489590	179.227550
Mid Qawa	WET	16.462900	179.463440
Upper Qawa	WET	16.478890	179.482960
Mid Labasa	WET	16.534500	179.388760
Upper Labasa	WET	16.559810	179.414320
Lutukina (Upper Dreketi)	WET	16.660900	178.989720