11-2011

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Kathy M. Maline
Nebraska Public Health Environmental Laboratory, Lincoln, NE, kathy.maline@nebraska.gov

Keith D. Koupal
Nebraska Game and Parks Commission, Kearney, keith.koupal@nebraska.gov

Brian C. Peterson
University of Nebraska Kearney, petersonbc@unk.edu

W. Wyatt Hoback
University of Nebraska at Kearney, whoback@okstate.edu

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Kathy M. Maline[1], Keith D. Koupal[2], Brian C. Peterson[3], W. Wyatt Hoback[3]

[1]Nebraska Public Health Environmental Laboratory, 3701 South 14th Street, Lincoln, Nebraska 68502

[2]Nebraska Game and Parks Commission, 1617 1st Avenue, Kearney, Nebraska 68847

[3]Department of Biology, University of Nebraska at Kearney, 2401 11th Avenue, Kearney, Nebraska 68849-1140

Correspondence: Kathy Maline, kathy.maline@nebraska.gov, 402-598-4515

The objective of this study was to determine the horizontal and vertical distribution of zooplankton in Harlan County Reservoir in order to assist in developing an appropriate zooplankton sampling regime for this and similar Nebraska irrigation reservoirs. Samples were collected at 16 sites distributed across 3 zones of the reservoir monthly in April, May, June, and July of 2007 using a 2.2 L Van Dorn sampler. Samples were collected at depths of 1, 4, and 7 meters, poured through an 80-µm filter, preserved, and identified to the lowest possible taxa. Total zooplankton densities in Harlan County Reservoir were statistically similar for samples collected at 1 m, 4 m, and 7 m of depth from April, June, and July samples. Samples collected in May had significantly more zooplankton at 1 m of depth ($F = 6.98$; $p \leq 0.01$) compared to 4 m and 7 m. Density of total zooplankton collected at 1 m depth from pelagic and littoral sites in zone 1 was similar among months. Also, zooplankton densities were similar from the upper, middle, and lower regions of Harlan County Reservoir in all four sample months. These results indicate that zooplankton distribution in Harlan County Reservoir have a homogeneous vertical and horizontal distribution.

Introduction

Zooplankton are a critical component of freshwater aquatic food webs. Loss of larger cladoceran species can reduce grazing pressure on lower trophic level phytoplankton which can induce algal blooms that may eventually disrupt the function of the ecosystem (Moss *et al.* 1997, Muyalaert *et al.* 2005). Higher trophic levels such as planktivorous fish also can exhibit decreased survival when zooplankton densities are reduced (Mills and Schiavone 1982).

Patterns in the distribution of zooplankton are well recognized, but not always consistent among different systems. Diel vertical migration driven mainly by predation and damaging ultraviolet radiation is a common occurrence (Dini and Carpenter 1992, Lienesch and Matthews 2000, Lampert *et al*. 2003). Variability in species assemblage and density of zooplankton on a horizontal scale has also been reported in multiple systems (Wurtsbaugh and Li 1985, Patalas and Salki 1993, Geraldes and Boavida 2004, Viljanen *et al.* 2009). However, Livings *et al.* (2010) reported homogenous distribution in two midwestern lakes. Physical processes such as wind (Jones *et al.* 1995) can drive the distribution of small aquatic organisms and disruption of normal vertical distribution of zooplankton has been attributed to down-welling and internal waves (Rinke *et al.* 2007).

Investigations on the relevance of spatial and temporal scales to food webs have recently become more prevalent (Woodward and Hildrew 2002, Mehner *et al.* 2005). Any attempt to better understand the food web of an aquatic system must develop an awareness of how best to sample the various trophic levels of that system. Identifying distributions of organisms from different trophic levels along with associated physical and chemical components represents the beginning tenets for developing an ecological model. However, prior to gathering data to assess the composition and abundance of zooplankton, it is essential to determine distribution patterns, in order to establish an appropriate sampling regime.

This study was designed as a component of an on-going limnological assessment of Harlan County Reservoir. The objective of this study was to investigate the vertical and horizontal distribution of the zooplankton community within Harlan County Reservoir. Results will assist in developing appropriate sampling regimes for this reservoir and similar Nebraska irrigation reservoirs that are mixed by wind and resulting internal waves.

Study Site

Harlan County Reservoir is located in south-central Nebraska near the Kansas border. The U.S. Army Corps of Engineers manages the 5,362 ha (at full pool) reservoir (USACE 2008). The sportfish community is managed for walleye (*Sander vitreus*) and white bass (*Morone chrysops*) with gizzard shad (*Dorosoma cepedianum* (Lesueur)) as the dominant planktivore. Harlan County Reservoir has a mean depth of 4 m and a maximum depth of 18 m (Olds 2007) and because of high winds experiences infrequent and weak thermal stratification in June and July (USACE 2008). Thermal stratification was not observed during sampling months for this project (Koupal and Peterson 2008). The lake is considered eutrophic and the main water quality concerns are excess nutrients, sediments, and the occurrence of toxic cyanobacteria blooms (USACE 2008).

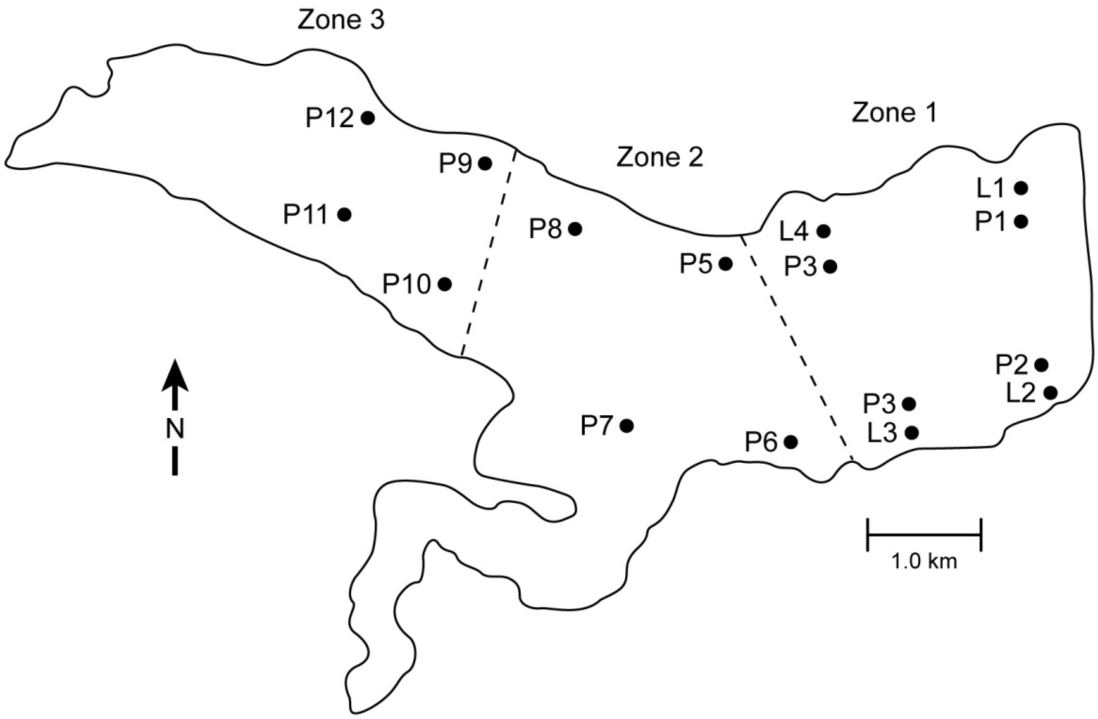

Figure 1. Map of Harlan County Reservoir Showing 16 Sampling Sites.
Sites labeled L (littoral) are where water depth was ≤2 m. Sites labeled P (pelagic) are where the water depth is >4 m.

Methods
Harlan County Reservoir was divided from east to west into three zones with a total of sixteen sites sampled across all zones (Figure 1). All three zones had four pelagic sampling sites with an additional four littoral sites sampled in zone 1. Zooplankton were collected on the same date between 0900-1300 one time per month from April through July, 2007 using a 2.2 L Van Dorn bottle sampler at 1 m, 4 m, and 7 m depending on the depth at the site. Samples from 1 m depth were collected at all sixteen sites, while 4 m samples were collected from eight pelagic sites in zone 1 and 2, and 7 m samples were collected from four pelagic sites in zone 1. Collected samples were poured through an 80-µm filter and zooplankton were preserved in a 4% formalin sucrose solution (Haney and Hall 1973). All zooplankton collected were identified to the lowest possible taxon using a compound microscope. Total number of zooplankton were recorded and mathematically converted to the number of zooplankton per liter for analysis.

The samples were grouped by depth for each sampling date. A one-way ANOVA was performed for each date to test for differences in the mean zooplankton collected at each depth. If differences were detected, a Tukey test was used to test differences among means. The 1 m samples collected in zone 1 were also grouped as pelagic and littoral based on the location where they were collected. The pelagic and littoral (1 m) samples were compared using a Student's t-test to test for differences in the mean zooplankton per liter for each sampling date. The data for copepods, cladocerans, nauplii and *Daphnia* taxa were grouped by depth and separated by date. The data for each sampling date were analyzed using a one-way ANOVA in order to identify differences in taxa groups for each depth. Zooplankton density by zone analysis was assessed for each date by comparing zooplankton densities from 1 m samples collected in each designated zone. When differences were detected, a Tukey test was used to separate means.

Results
Total zooplankton densities in Harlan County Reservoir were statistically similar from April, June, and July samples (Table 1). Samples collected in May had significantly more zooplankton at 1 m of depth (F = 6.98; $p \leq 0.01$) compared to 4 m and 7 m. Vertical segregation of specific taxa groups was also limited in the samples collected in Harlan County Reservoir (Table 1). Total adult copepods were statistically more prevalent at 1 m of depth in May (F = 9.72; $p \leq 0.01$) and at 7 m of depth in July (F = 7.53; $p \leq 0.01$). These differences were driven by calanoid copepods not cyclopoids, which did not differ at any depth during the season. *Daphnia retrocurva* were statistically more abundant at 4 m of depth compared to 1 m of depth in July (F = 11.81; $p \leq 0.01$).

Table 1. The Mean (± Standard Error) for Zooplankton Taxa per Liter in Harlan County Reservoir[1].

	Month	1 m	4 m	7 m	F	p
Total Zooplankton	April	91.73 (8.67)	80.00 (7.48)	75.91 (5.25)	0.71	0.50
	May	**103.52 (8.59)[a]**	**79.03 (6.18)[b]**	**46.93 (4.67)[b]**	6.98	<0.01
	June	82.96 (12.63)	75.51 (12.09)	44.43 (4.36)	1.27	0.29
	July	58.84 (5.51)	58.86 (2.99)	54.43 (2.95)	0.11	0.90
Total *Daphnia*	April	31.39 (4.03)	30.51 (3.25)	22.39 (5.17)	0.23	0.97
	May	22.59 (4.46)	15.91 (3.30)	13.30 (4.52)	0.91	0.42
	June	21.80 (7.73)	12.44 (2.14)	6.48 (1.62)	0.83	0.45
	July	9.72 (1.66)	10.00 (1.00)	4.55 (0.79)	1.65	0.21
D. pulicaria	April	9.80 (1.36)	9.72 (1.23)	6.71 (1.36)	0.74	0.49
	May	8.72 (1.95)	7.22 (1.15)	9.32 (3.96)	0.17	0.84
	June	**0.88 (0.20)[a]**	**1.93 (0.51)[b]**	**2.96 (0.29)[b]**	9.00	<0.01
	July	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	n/a	n/a
D. retrocurva	April	21.59 (3.19)	20.80 (2.45)	15.68 (5.32)	0.45	0.64
	May	13.86 (2.83)	8.69 (2.26)	3.98 (1.04)	2.09	0.14
	June	20.85 (7.69)	10.51 (2.20)	3.52 (1.52)	1.06	0.36
	July	**2.02 (0.46)[a]**	**5.85 (0.75)[b]**	**4.09 (0.53)[ab]**	11.81	<0.01
D. lumholtzi	April	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	n/a	n/a
	May	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	n/a	n/a
	June	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	n/a	n/a
	July	7.70 (1.48)	4.15 (1.10)	**0.46 (0.26)[a]**	4.08	0.03
Adult Copepods	April	39.52 (6.54)	31.53 (3.50)	31.71 (6.51)	0.46	0.63
	May	**50.80 (5.28)[a]**	**29.55 (3.02)[b]**	**13.07 (1.83)[c]**	9.72	<0.01
	June	31.45 (3.97)	33.30 (7.12)	14.55 (1.60)	2.01	0.15
	July	17.44 (2.87)	21.19 (1.91)	**38.86 (4.64)[a]**	7.53	<0.01
Calanoida	April	23.67 (3.08)	20.57 (2.14)	19.77 (3.27)	0.37	0.69
	May	**39.38 (4.95)[a]**	**23.01 (2.78)[b]**	**11.25 (1.62)[c]**	6.28	<0.01
	June	23.24 (3.31)	23.47 (5.61)	10.11 (1.21)	1.69	0.20
	July	11.36 (2.48)	14.26 (1.65)	**31.82 (3.49)[a]**	9.48	<0.01
Cyclopoida	April	15.85 (3.82)	10.97 (1.86)	11.93 (3.34)	0.47	0.63
	May	11.42 (2.37)	6.53 (1.65)	1.82 (0.67)	2.86	0.08
	June	8.21 (1.41)	9.83 (3.25)	4.43 (0.68)	0.91	0.42
	July	6.08 (1.16)	6.93 (1.17)	7.05 (1.36)	0.16	0.85
Nauplii	April	13.95 (1.42)	13.07 (2.31)	14.43 (3.01)	0.09	0.91
	May	27.02 (1.82)	30.34 (1.55)	**19.21 (2.93)[a]**	4.02	0.03
	June	24.74 (3.02)	22.61 (3.00)	18.86 (2.61)	0.52	0.60
	July	29.32 (2.96)	25.11 (3.77)	**8.07 (1.75)[a]**	6.14	<0.01

[1]Collected with a Van Dorn sampler at 1, 4, and 7 m for each sampling month in 2007. Sample sizes for 1 m, 4 m, and 7 m were 16, 8, and 4, respectively. Significant differences are indicated with superscript letters and bold print.

Daphnia lumholtzi (F = 4.08; p = 0.03) and nauplii (F = 6.14; p < 0.01) were statistically less abundant at 7 m of depth compared to 1 m and 4 m of depth in July. *Daphnia pulicaria* were significantly less abundant at 1 m compared to 4 m and 7 m in June (F = 9.00; $p \leq 0.01$). No detectable differences occurred for all remaining comparisons for vertical distribution of taxa groups by depth within each of the study months. We did not detect differences in the distribution of total zooplankton throughout the reservoir and throughout the scope of this study. The density of total zooplankton from pelagic and littoral sites in zone 1 at one meter of depth was similar among months (Table 2). Overall densities were slightly higher in pelagic samples in June and July. Zooplankton densities across the zones in Harlan County Reservoir showed no statistical differences (Table 3). Densities varied through time with zone 3 (farthest from the dam) showing the greatest densities in April and June. The highest density of zooplankton in May was found in zone 1.

Discussion

The zooplankton community of Harlan County Reservoir displayed a homogenous vertical distribution in three of the four sample months. The trend appears to indicate a greater density of zooplankton in the upper 1 m of the water column; however, the variability among samples from the same depth was high. Additionally, the study sample design has variable numbers of sites from each depth, which reduces the ability to detect significant differences. Previous research in a well-mixed lake that is not thermally stratified and where gizzard shad are the dominant planktivore showed inconsistent distributions of zooplankton during both day and night (Fejes *et al*. 2003).

Positioning of zooplankton near the surface can be advantageous as warmer water temperatures are more conducive to growth and their main food supply (phytoplankton) is found at the surface

Table 2. Zooplankton at 1 m in Zone 1[1].

Month	Littoral	Pelagic	*t*	*p*
April	83.98 (10.44)	90.23 (13.84)	–0.39	0.72
May	118.30 (26.94)	111.36 (10.74)	0.43	0.70
June	47.05 (5.04)	61.27 (18.99)	–0.72	0.52
July	38.41 (8.97)	63.64 (1.86)	–2.39	0.10

[1]The mean (± standard error) number of zooplankton per liter collected at 1 m in Zone 1 of Harlan County Reservoir. Littoral samples (n=4) were collected where the reservoir was ≤2 m deep. Pelagic samples (n=4) were collected where the reservoir was greater than 4 m in depth.

Table 3. Zooplankton at 1 m in Zones 1, 2, and 3[1].

Month	Zone 1	Zone 2	Zone 3	*F*	*p*
April	90.23 (13.84)	84.32 (11.38)	108.41 (30.66)	0.38	0.70
May	111.36 (10.74)	96.82 (18.22)	87.61 (10.50)	0.77	0.49
June	61.14 (19.00)	83.98 (7.79)	139.66 (32.92)	3.24	0.09
July	63.64 (1.86)	65.68 (13.00)	67.61 (41.11)	0.03	0.97

[1]The mean (± standard error) number of zooplankton per liter collected at 1 m of depth in Zones 1, 2, and 3 of Harlan County Reservoir for each sampling month of 2007. Eight sites were sampled for zone 1 and four for zones 2 and 3. The same sites were sampled each month.

(Lampert 1989, Dini and Carpenter 1992, Loose and Dawidowicz 1994, Lampert *et al.* 2003). Often zooplankton communities exhibit diel vertical migration where they reside in deeper depths during daylight hours and migrate higher in the water column to feed at night. Diel vertical migration typically develops as an adaptation to predation and ultra-violet radiation, but can also be affected by food availability, temperature, light intensity and turbidity (Gliwicz 1986, Leibold 1990, Bollens and Frost 1991, Rhode *et al.* 2001, Alonso *et al.* 2004, Kubar *et al.* 2005, Leech *et al.* 2005). Finding slightly more zooplankton closer to the surface in Harlan County Reservoir suggests that zooplankton are either not conducting diel vertical migration or are conducting finer migrations between one and four meters. Alternatively, distribution of zooplankton may be driven by wind mixing and resulting internal waves (Gliwicz 1986, Leibold 1990, Bollens and Frost 1991, Loose and Dawidowicz 1994).

Horizontal distribution of zooplankton in Harlan County Reservoir was also homogenous. Two monthly samples showed greater zooplankton densities in zone 3 although variability of collected samples was high. In May, the trend was reversed with the greatest number of zooplankton collected in zone 1 and the least in zone 3. Zone 3 is shallower and has a higher concentration of nutrients and chlorophyll *a* and has been shown to consistently have higher densities of gizzard shad and zooplankton (Olds 2007). Zooplankton densities increase as phytoplankton concentrations increase and are more numerous at reservoir stations farther from the dam where turbidity is greater (Kochsiek *et al.* 1971, Ka *et al.* 2006). The reversal in May could be a response to the emergence of larval gizzard shad in zone 3 at that time (Olds 2007).

Density of zooplankton at 1 m was similar in littoral and pelagic areas of Harlan County Reservoir. Olson *et al.* (2004) found littoral areas of lakes held more cyclopoids and *Daphnia* than pelagic areas and suggested the presence of vegetation may be beneficial to certain species. Copepods can utilize aquatic vegetation as a way to hide from predators (Flinn *et al.* 2005). However, in Harlan County Reservoir the frequent fluctuations of water level often preclude the development of substantial aquatic macrophytes, which may account for the lack of differences between littoral and pelagic zooplankton densities.

This research provides insight into the distribution of the zooplankton community in Harlan County Reservoir during the year sampling was conducted. The dates sampled during this project demonstrated that zooplankton were predominately homogenous in their vertical and horizontal distribution throughout the reservoir. Specific taxa groups such as calanoids and cyclopoids retreat deeper in the water column later in the summer while nauplii are deeper in the water column early in the spring, but close to the surface in mid to late summer. Sampling the entire vertical column would ensure that all components of the zooplankton community are adequately represented. The development of a sampling regime to monitor zooplankton populations in Harlan County Reservoir and similar irrigation reservoirs in the Midwest should be more concerned with the number of sites needed to overcome the high variability between samples rather than the distribution of the sample sites.

Acknowledgements

We thank Dr. Kerri Farnsworth-Hoback and Dr. Marc Albrect for their valuable contributions to this work. Thanks, also, to Brett Olds and Grant Sorenson who participated in the sampling and Rick Simonson for modifying and contributing the lake figure to this manuscript. Partial support for this project was provided by the University of Nebraska at Kearney Research Services Council and the Nebraska Game and Parks Commission.

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