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Managing Water in the West

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Evaluating the Cost Effectiveness of Data Collection Techniques and Relative Improvements in Modeling Reservoir Production

U.S. Department of the Interior
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U.S. DEPARTMENT OF THE INTERIOR

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14. ABSTRACT *(Maximum 200 words)*

The study documented the contributions of two phytoplankton groups, a diatom group and reservoir outflow estimates to the performance of a reservoir ecosystem model. Information from these analyses identified that adjusting for reservoir outflow reduced model error. The revised model parameters were utilized in subsequent analyses that rely on output from the reservoir ecosystem model (a three-dimensional (3D) hydrodynamic ELCOM-CAEDYM model) as a part of the larger Deadwood River study examining the effects of reservoir operations on reservoir and river ecosystem dynamics. This improved model performance was beneficial for other subsequent analyses that rely on output from the ELCOM-CAEDYM model.

15. SUBJECT TERMS

Examining the effects of reservoir operations on bull trout in the Deadwood Reservoir using data collected from the reservoir to calibrate and validate a combined physical-chemical and biological model to describe reservoir conditions using different reservoir operation scenarios.

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Peer Reviewer: I have reviewed the assigned items/sections(s) noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

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EXECUTIVE SUMMARY

In response to the Terms and Conditions outlined in the 2005 Biological Opinion for U.S. Bureau of Reclamation (Reclamation) Operations and Maintenance in the Snake River Basin above Brownlee Reservoir (USFWS 2005), Reclamation examined effects of reservoir operations on bull trout in the Deadwood Reservoir. This study utilizes data collected from the reservoir to calibrate and validate a combined physical-chemical and biological model to describe reservoir conditions using different reservoir operation scenarios. The hydrodynamic and aquatic ecological models, ELCOM and CAEDYM, were used in this study. Continuous, real-time data indicated that the predictions on temperature and dissolved oxygen were relatively accurate; however, the biological predictions were less precise. The initial model runs only included one phytoplankton group and did not include any zooplankton data which could be a source of substantial model uncertainty. However, ELCOM-CAEDYM can include up to seven phytoplankton groups and five zooplankton groups. Therefore, this study examined samples collected in Deadwood Reservoir in 2008 and 2009 to identify additional details about phytoplankton and zooplankton dynamics in the reservoir and identify and quantify model improvement. The research project focused on relative model improvements if taxonomic data, comprising the reservoir food base, are included versus using standard measured water quality constituents, obtained and processed at a lesser cost to parameterize the reservoir processes.

Five sites (DEA004, DEA006, DEA010, DEA014, DEA016) were sampled approximately biweekly from June through September in 2008 and 2009 (Table 1 and 2). Site DEA010 was sampled approximately weekly in 2008. On July 30, 2008, night samples (12:00 – 2:00 am) were collected to examine change in community composition due to diurnal vertical migration. On August 12 through 14, 2008, samples from four additional sites (DEA050, DEA051, DEA052, DEA053) were obtained to examine spatial variability in plankton community composition. There was considerable variability in the biovolume and community composition in the phytoplankton and zooplankton in Deadwood Reservoir. Plankton community composition exhibited high temporal variation across seasons and years sampled. Based on these data, the CAEDYM model was adjusted to include two different phytoplankton groups – a eutrophic cyanobacteria group and a diatom group. Inclusion of the new CAEDYM configuration ("New CAEDYM config") compared to the original ("Original") configuration saw marginal improvements in all chlorophyll-a metrics. The mean average error (MAE) and the root mean square error (RMSE) were reduced by approximately 5 percent, and model skill increased by 7 percent; however, this was not a substantial improvement in the model performance. Therefore, researchers searched for additional opportunities to improve model performance and identified that the model predictions were most sensitive to outflow measurement. Accounting for outflow measurement error, as well as the additional phytoplankton groups, resulted in measureable model improvements in temperature, dissolved oxygen, and chlorophyll-a (measured as model skill, mean average error and root mean square

error). Model skill for temperature increased from 0.96 to 0.99 and the model error is less than 1C. Dissolved oxygen model skill improved from 0.65 to 0.76 (17 percent improvement) and error was reduced 13 to 17 percent). Model skill for chlorophyll-a increased by 26 percent and error decreased between 4 and 17 percent.

In summary, this study documented model prediction improvements when including two phytoplankton groups and a diatom group in the CAEDYM model while adjusting the model to account for outflow measurement error. These improvements were incorporated into the final model utilized in a larger Deadwood River study examining the effects of reservoir operations on reservoir and river ecosystem dynamics. This improved model performance was beneficial for other subsequent analyses that rely on output from the ELCOM-CAEDYM model. More generally, improvements in the data and model tools related to ecosystem science will assist managers when evaluating reservoir operations and improve predictions of conditions to fish and other species of interest.

Acronyms and Abbreviations

μm^3	cubic micrometer
ANOVA	analysis of variance
cfs	cubic feet per second
chla	chlorophyll a
EPA	Environmental Protection Agency
LDS	Lake Diagnostic System
m^3	cubic meter
MAE	mean average error
MDS	multidimensional scaling
mL	milliliter
Opinion	USFWS Biological Opinion
PERMANOVA	permutational analysis of variance
Reclamation	U.S. Bureau of Reclamation
RMSE	root mean square error
USFWS	U.S. Fish and Wildlife Service
µg chla	micrograms of chlorophyll-a
µm	micrometer

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INTRODUCTION

The Bureau of Reclamation (Reclamation) is committed to developing innovative water management tools and minimizing impacts of project operations on aquatic ecosystems. Water quality and ecosystem models can provide insight about effects of proposed changes in operations or system configuration. Mechanistic models, which represent physical, chemical, and/or biological processes explicitly, are particularly useful for inferring effects outside of the domain within which initial data were collected. Such models may be complex in terms of system representation and data needs. Obtaining high quality data that adequately represent the system is critical since model predictions depend on these data.

In response to Terms and Conditions in the 2005 *Biological Opinion for Reclamation Operations and Maintenance in the Snake River Basin above Brownlee Reservoir* (USFWS 2005), Reclamation examined effects of reservoir operations on bull trout in the Deadwood Reservoir. The modeling approach of Saito et al. (2001) was applied to describe links between reservoir operations, phytoplankton production, and energy available for bull trout production in the Deadwood Reservoir. The hydrodynamic and aquatic ecological models ELCOM and CAEDYM (Figure 1) were used to describe physical, chemical, and biological components of the Deadwood Reservoir and predict how reservoir conditions change with alternative reservoir operations. Trophic linkages from phytoplankton to fish (Figure 2) were quantified using stable isotope analysis. Finally, net phytoplankton energy available for each operational scenario was propagated through the modeled food web to estimate growth potential for bull trout and other fish. These studies are described in detail in Reclamation's *Deadwood Reservoir Operations Flexibility Evaluation* report (Reclamation 2015).

Physical and chemical monitoring of Deadwood Reservoir was conducted to calibrate ELCOM-CAEDYM, including continuous, real-time measurement of temperature and dissolved oxygen and biweekly measurement of water quality variables. Biological sampling initially consisted of biweekly sampling of chlorophyll-a and phytoplankton biomass at three sites. ELCOM-CAEDYM can include up to seven phytoplankton groups and five zooplankton groups. Initially, algal groups were not identified taxonomically, rather, reservoir phytoplankton were modeled as a single group in ELCOM-CAEDYM. This single group represented the entire phytoplankton assemblage. Similarly, in initial modeling efforts zooplankton were estimated using uncalibrated parameters. Representation of phytoplankton as a single group and total lack of data on zooplankton had potential to cause significant model uncertainty.

Science and Technology funds were used to sample and identify major groups of phytoplankton and zooplankton in Deadwood Reservoir so that biotic community structure could be modeled more precisely. The value of plankton taxonomy data for improving model predictions was examined. Our goal was to improve modeling of the Deadwood system and inform sampling protocols in other systems where these models are implemented.

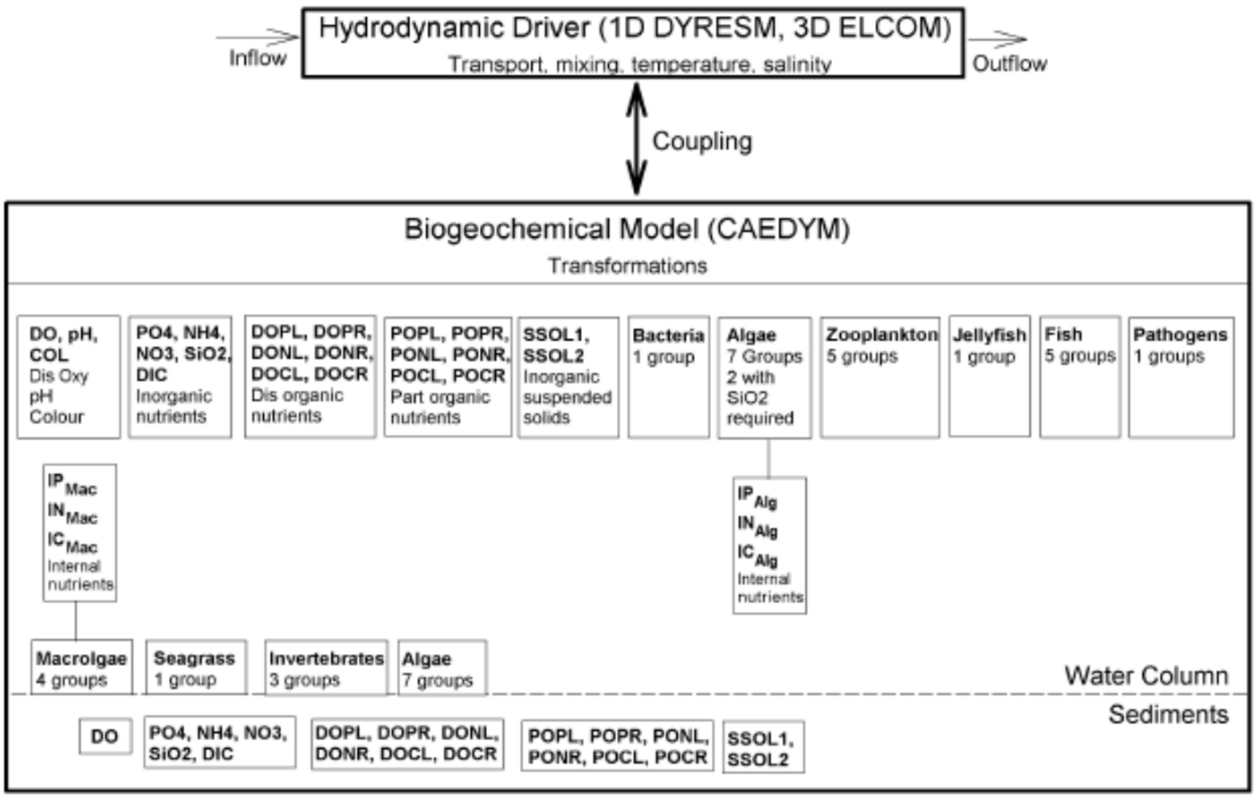

Figure 1. Overview of CAEDYM state variables showing water, benthic, and sediment components (Hipsey, Antenucci, and Hamilton 2012).

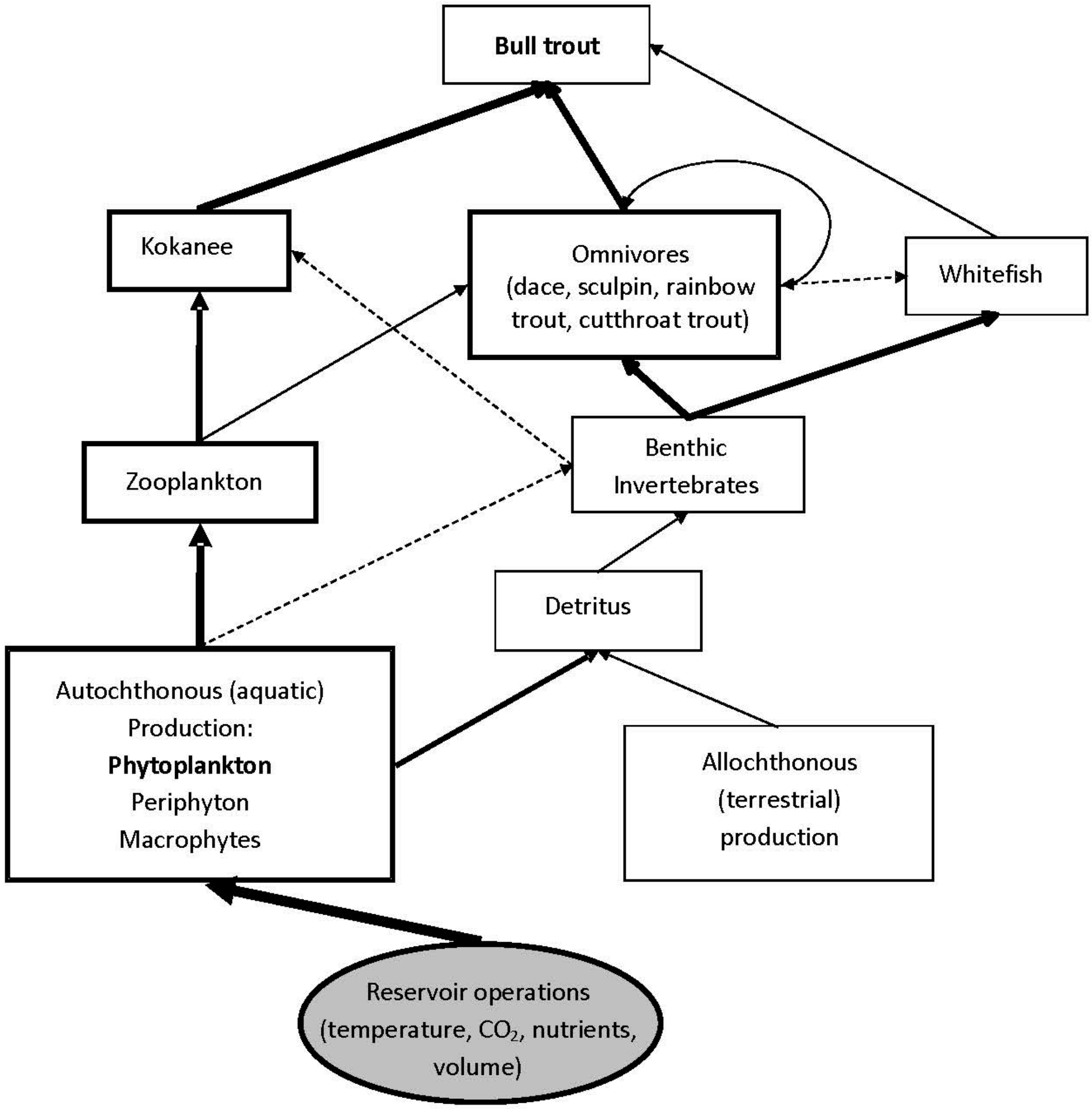

Figure 2. Conceptual model of the Deadwood Reservoir food web. Arrow thickness represents a-priori expectations for relative importance of trophic pathway for energy transfer. Dashed lines indicate linkages that may not contribute significantly to energy transfer through the food web.

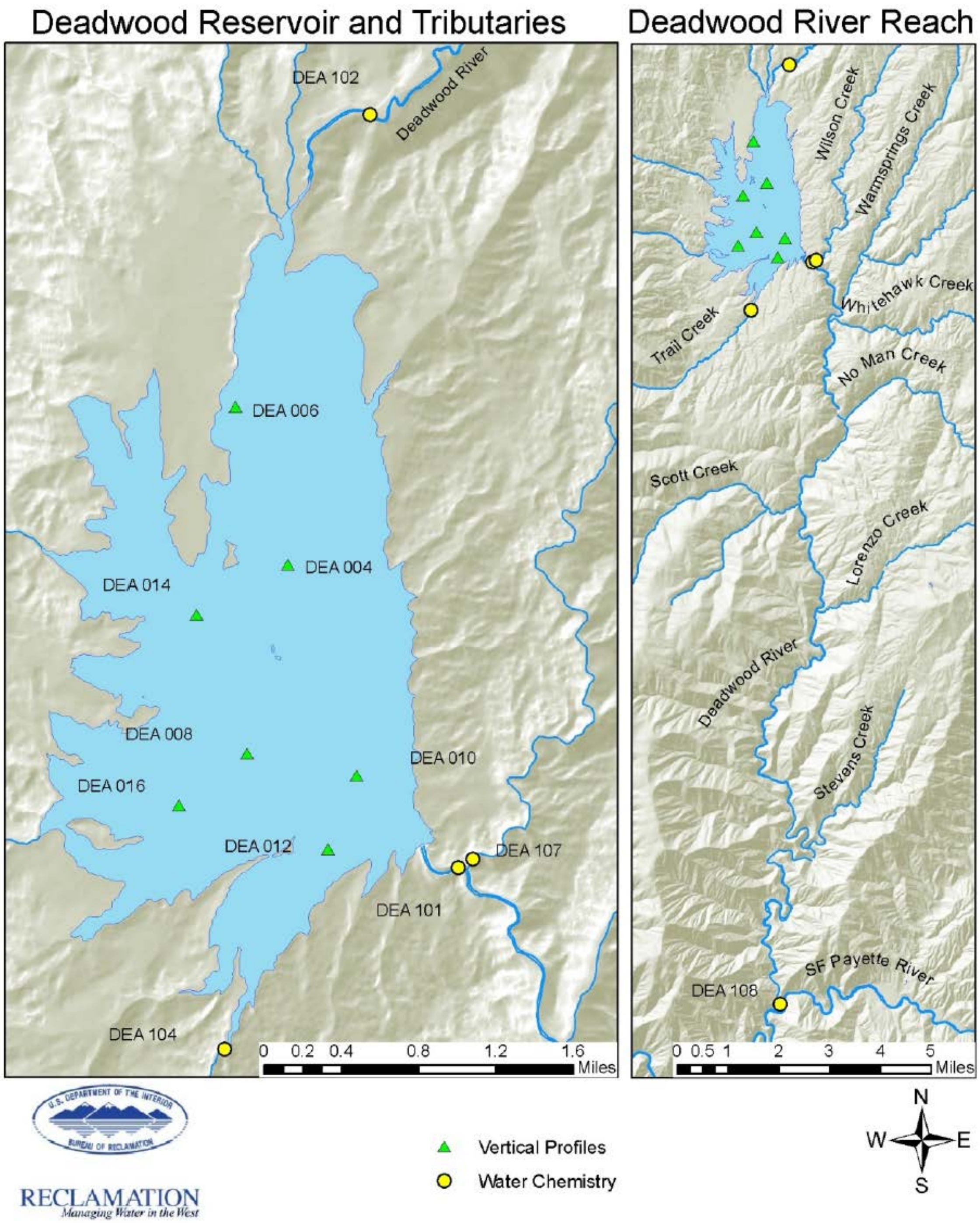

Figure 3. Deadwood Reservoir and River with sampling sites for the ELCOM-CAEDYM and food web energy transfer models.

METHODS

ELCOM v2.2 (Hodges and Dallimore 2012) and CAEDYM v3.2 (Hipsey et al 2012) were used to model the Deadwood Reservoir in three dimensions (Figure 1). ELCOM and CAEDYM are dynamically coupled and include comprehensive process representation of density stratification, flow, thermal structure, major elemental cycles (C, N, P, Si, and DO), inorganic suspended solids, and phytoplankton dynamics. CAEDYM state variables occur in water column, benthic, and sediment components. Model calibration and validation steps rely on data about reservoir level, weather conditions, water temperature, water chemistry, phytoplankton biomass, tributary inflows, and reservoir releases. Details on all models used in Deadwood Reservoir are in the *Deadwood Reservoir Operations Flexibility Evaluation* report (Reclamation 2015).

Sampling for Plankton

Physical modelling and water quality data for Deadwood Reservoir demonstrate very little variability across space in the Deadwood Reservoir (Reclamation 2015). Given this observation, sampling emphasized describing temporal rather than spatial variability. Five sites (DEA004, DEA006, DEA010, DEA014, DEA016) were sampled approximately biweekly from June through September in 2008 and 2009 (Tables 1-2). Site DEA010 was sampled approximately weekly in 2008. On July 30, 2008, night samples (12:00 – 2:00 am) were collected to examine change in community composition due to diurnal vertical migration. On Aug 12 – 14, 2008 samples from four additional sites (DEA050, DEA051, DEA052, and DEA053) were obtained to examine spatial variability in plankton community composition.

Zooplankton. A zooplankton net was pulled through the water column vertically from a known depth at a constant rate (1 m / second) so an estimate of sample volume was determined. A flow meter was not used during zooplankton net hauls, but the time pulling the net was recorded. Zooplankton were concentrated with a 75 µm mesh sieve, narcotized in CO2 and preserved in 90 percent ethanol. Approximately 200 to 400 microcrustacea and rotifers from each sample were counted and identified to lowest practical taxonomic level (typically genus or species) by EcoAnalysts, Inc. (Moscow, Idaho). Length measurements were taken on the first 20 units for dominant taxa and five units for minor taxa. From these length measurements, average biovolume was calculated for each taxon, without reference to sample date or site. Using these data and estimated water volume sampled, we calculated zooplankton taxa abundance per cubic meter (# individuals / m^3) and taxa biovolume per cubic meter (μm^3/ m^3) of water.

Phytoplankton. Water samples were collected from the photic zone using an integrated tube sampler and stored for 0 – 5 hours in cool, dark carboys. In 2008, samples were poured through an 80 µm sieve to remove large zooplankton, mixed thoroughly, and a 500 mL aliquot was preserved in 1 percent Lugol’s solution and stored in the dark. In 2009, large zooplanktons were not removed from the sample before preservation, in order to include larger colonial algae in the sample. Taxonomists at EcoAnalysts, Inc. (Moscow, Idaho) identified phytoplankton in samples using standard methods for U.S. Environmental Protection Agency Lakes Surveys. Both soft-bodied forms and diatoms were identified in all samples.

Table 1. Summary of zooplankton samples (55 total) analyzed for community composition.**

Year	Date	DEA004	DEA006	DEA010	DEA014	DEA016	Total
2008	16-Jul	1	1	1	1	1	5
	30-Jul	1	1	1	1	1	5
	31-Jul	1*	1*	1*	1*	1*	5
	13-Aug	1	1	1	1	1	5
	26-Aug			1			1
	11-Sep			1			1
2009	17-Jun	1	1	1	1	1	5
	24-Jun	1	1	1	1	1	5
	8-Jul			1			1
	22-Jul			1			1
	5-Aug			1			1
	19-Aug	1	1	1	1	1	5
	2-Sep			1			1
	16-Sep	1	1	1	1	1	5
	30-Sep	1	1	1	1	1	5
	Total	9	9	15	9	9	51*

* Night samples.
**In addition to the primary sampling sites, samples from DEA050, DEA051, DEA052, DEA053 (1 each, taken August 13, 2008) were analyzed but are not reported here.

Table 2. Summary of phytoplankton samples (58 total) analyzed for community composition.**

Year	Sample Date	DEA004	DEA006	DEA010	DEA014	DEA016	Total
2008	17-Jul	1	1	1	1	1	5
	30-Jul	1	1	1	1	1	5
	31-Jul	1*	1*	1*	1*	1*	5
	13-Aug	1	1	1	1	1	5
	26-Aug			1			1
	10-Sep	1	1	1	1	1	5
2009	17-Jun	1	1	1	1	1	5
	24-Jun	1	1	1	1	1	5
	8-Jul			1			1
	22-Jul			1			1
	5-Aug			1			1
	19-Aug	1	1	1	1	1	5
	2-Sep			1			1
	16-Sep	1	1	1	1	1	5
	30-Sep	1	1	1	1	1	5
	Total	10	10	15	10	10	55*

*Night samples.
**In addition to the primary sampling sites, samples from DEA050, DEA051, DEA052 (1 each, taken 13 August 2008) were analyzed but are not reported here.

Community Composition Analysis

The PRIMER statistical package was used for data visualization and analysis of zooplankton community composition (PRIMER v6; Clarke and Gorely 2006). A Bray-Curtis similarity matrix was constructed to describe differences in zooplankton abundance and biovolume between samples. A permutational analysis of variance (PERMANOVA; Anderson 2001) was used to test for spatial and temporal differences in community composition. PERMANOVA is a useful for analyzing community composition data because it partitions variance like other analysis of variance (ANOVA) methods, but also provides the flexibility and robustness of non-parametric methods. The PERMANOVA test statistic is based on permutation, and represents the probability of observing the differences present among groups that were sampled.

Differences in zooplankton community composition data were examined using nonmetric multidimensional scaling (MDS) (Clarke and Warwick 2001; McCune and Grace 2002). MDS is an iterative optimization method that attempts to find the configuration of points that minimizes stress between similarity rankings and corresponding distance rankings in a plot. A Kruskal's stress value is associated with each plot. A value of less than 0.1 corresponds to a good representation without a large chance of misinterpretation.

Temporal variation in zooplankton was examined by graphing abundance and biovolume of the dominant taxa at the primary reservoir sampling site (DEA010).

Phytoplankton Analysis and CAEDYM improvements

Phytoplankton were sampled to assist in CAEDYM simulations of chlorophyll-a. The CAEDYM model allows for the configuration of multiple phytoplankton groups. While up to five groups have been used in the past (Gal et al 2009), for most applications the number is limited to three by data availability and system understanding. The groups are flexible in their configuration, and can be used to describe a phyla (e.g., "diatoms"), an order (e.g., "centric diatoms"), a genus (e.g., "Aulacoseira sp.") or a species (e.g., "Aulacoseira granulata"). It is common to mix the use of the groups, where one group may be used to broadly represent diatoms, and another used to represent a species of filamentous cyanobacteria. The combination and configuration chosen is primarily based on the objectives of the study, the data and experience in similar systems.

Previous simulations of the Deadwood Reservoir, configured prior to the receipt of phytoplankton count data, had two groups configured – one representative of a diatom group, and one representative of a eutrophic chlorophyte group. This was based on expert knowledge, interpretation of the chlorophyll-a signal (timing and magnitude) and experience with similar systems. The data collected were grouped according to various methods to understand the temporal and spatial dynamics, in order to improve the representation of the phytoplankton groups chosen and thus reduce uncertainty in subsequent model predictions.

Model Performance

To quantitatively assess model performance due to changes implemented as above, four metrics were used:

1. **Correlation coefficient (r2)**. A simple correlation between all measurements for a particular variable, and the simulated values at the same depths and times. Varies between 0 and 1.
2. **Index of agreement** (Willmott 1982). This metric takes a value between 0 and 1, where 1 indicate perfect agreement between measured and simulation, and 0 indicates no agreement.
3. **Mean Average Error (MAE**). The mean absolute difference between measured and simulated values. Has the same unit as the variable being analyzed, and a lower value indicates a more accurate result.
4. **Root Mean Square Error (RMSE)**. The square root of the mean of the squared difference between measured and simulated values. Has the same unit as the variable being analyzed, and a lower value indicates a more accurate result.

In this context, measurements were used from the profiler for temperature, dissolved oxygen and chlorophyll-a at station DEA010. Over the course of the simulation period (2007-2008), a total of 888 measurements (i.e., N = 888) were made at varying depths and times. The values for temperature, dissolved oxygen and chlorophyll-a were extracted from the model at the same depths and times to make a direct quantitative comparison.

RESULTS AND DISCUSSION

Zooplankton community analysis

Fifty-five zooplankton samples were analyzed (Table 1). There was no significant difference in zooplankton community composition between sites (PERMANOVA, abundance: P = 0.7795; biovolume: P=0.1604; Table 3). There was a significant difference in zooplankton community composition between sampling dates (PERMANOVA, abundance: P = 0.0001; biovolume P=0.0001; Table 3).

MDS was used to examine community differences in abundance (Figure 4) and biovolume (Figure 5). Both MDS plots had a Kruskal's stress value less than 1.0 (abundance = 0.09, biovolume = 0.07), indicating a good representation of the data.

The MDS plot for zooplankton abundance showed large differences in samples between years (Figure 4). There was separation in ordination space by month within years, with July and August samples closer to each other, regardless of site. Night and day samples taken at the five primary sample sites in July, 2008, were similar. In August, 2008, samples were collected from four sites (DEA050, DEA051, DEA 052, and DEA053) in addition to the five primary sampling sites, to examine spatial variability in zooplankton communities in the reservoir. Zooplankton communities at DEA050 and DEA052 were similar to samples from the primary sites, whereas communities at DEA051and DEA053 were less similar.

The MDS plot for zooplankton community composition based on biovolume (Figure 5) did not replicate the strong year effect that was shown for zooplankton community composition based on abundance (Figure 4). Instead, samples within a month tended to be most similar. Samples from adjacent months tended to be more similar than samples from more distant months, regardless of sample year. Night samples taken at the five primary sample sites (July 31, 2008) were similar to day samples in July. Samples taken from additional sites (DEA050, DEA051, DEA052, and DEA053) in August, 2008 were most similar to September, 2009 samples.

Table 3. Analyses and models used for PERMANOVA (9999 permutations) in PRIMER.

Analysis	Model Used	Type of Data	Factor Tested	Fixed or Random?	P-value
Zooplankton Community Composition	1-way PERMANOVA	Abundance	Site	Random	0.7795
			Date	Fixed	**0.0001**
		Biovolume	Site	Random	0.1604
			Date	Fixed	**0.0001**

Since community composition was not significantly different between sites, the primary sampling site (DEA010; the location of the Lake Diagnostic System or LDS) was used to analyze composition of all groups of taxa over time. Overall abundance of zooplankton was higher in 2009 than 2008 (Figure 6). This difference was due to a large number of rotifers, which dominated all samples in both years (>75 percent of abundance). Copepods (*Aglaodiaptomus spp*. <1 percent, other copepods 5 percent) and cladocerans (*Daphnia spp*. 5 percent, *Bosmina longirostris* 1 percent, *Holopedium gibberum* <1 percent) were present but in much lower numbers (Figure 6).

Considering biovolume rather than abundance, rotifers became negligible (< 5 percent of biovolume) while cladocerans (*Daphnia spp*., *B. longistirosis* and *H. gibberum*) dominated (Figure 7). *H. gibberum* (June – July) and later *Daphnia spp*. (July – September) dominated the community composition through all of the sample periods. There was variation between sample years, with *H. gibberum* remaining the dominant taxon later into July in 2008 than in 2009, before being succeeded by *Daphnia spp*. In 2009, *B. longistirosis* and especially *Aglaodiaptomus spp*. (a calanoid copepod) contributed to biovolume whereas in 2008 they had a minimal contribution (Figure 7).

As expected, zooplankton community composition did not vary spatially between sites on a given date. This supports the use of site DEA010 (LDS station) as a representative of the entire reservoir. There was a significant difference in community composition over time related to seasonal changes in taxa abundance and biovolume. Rotifers consistently dominated the abundance of all zooplankton samples in the Deadwood Reservoir but were negligible in terms of biovolume. Cladocerans (*Daphnia spp*. and *H. gibberum*) drove differences in community composition between dates, due to their larger body size compared to rotifers. *H. gibberum* contributed a large percent (45 – 90 percent) of the biovolume early in the summer but essentially disappeared from the community by early August. *Daphnia spp*. contributed to biovolume through the entire season, ranging from less than 10 percent biovolume in June to greater than 90 percent biovolume in August and September.

Like many zooplankton, *Daphnia spp*. and *H. gibberum* population patterns are regulated by food availability and predation pressure (Balcer, Korda, and Dodson 1984; Dodson and Frey 2001). Although *H. gibberum* is a known food source to fish (Stenson 1973), Tessier (1986) found they were less vulnerable to fish predation than *Daphnia spp*., most likely due to the gelatinous sheath that surrounds them. *H. gibberum* are more sensitive to food scarcity however, thus spring increases in *H. gibberum* followed by a rapid decline in summer are likely due to starvation (Tessier 1986). Abiotic factors, such as pH and calcium concentrations have also been shown to influence *H. gibberum* and *Daphnia spp*. populations (Hessen, Faafeng, and Anderson 1995).

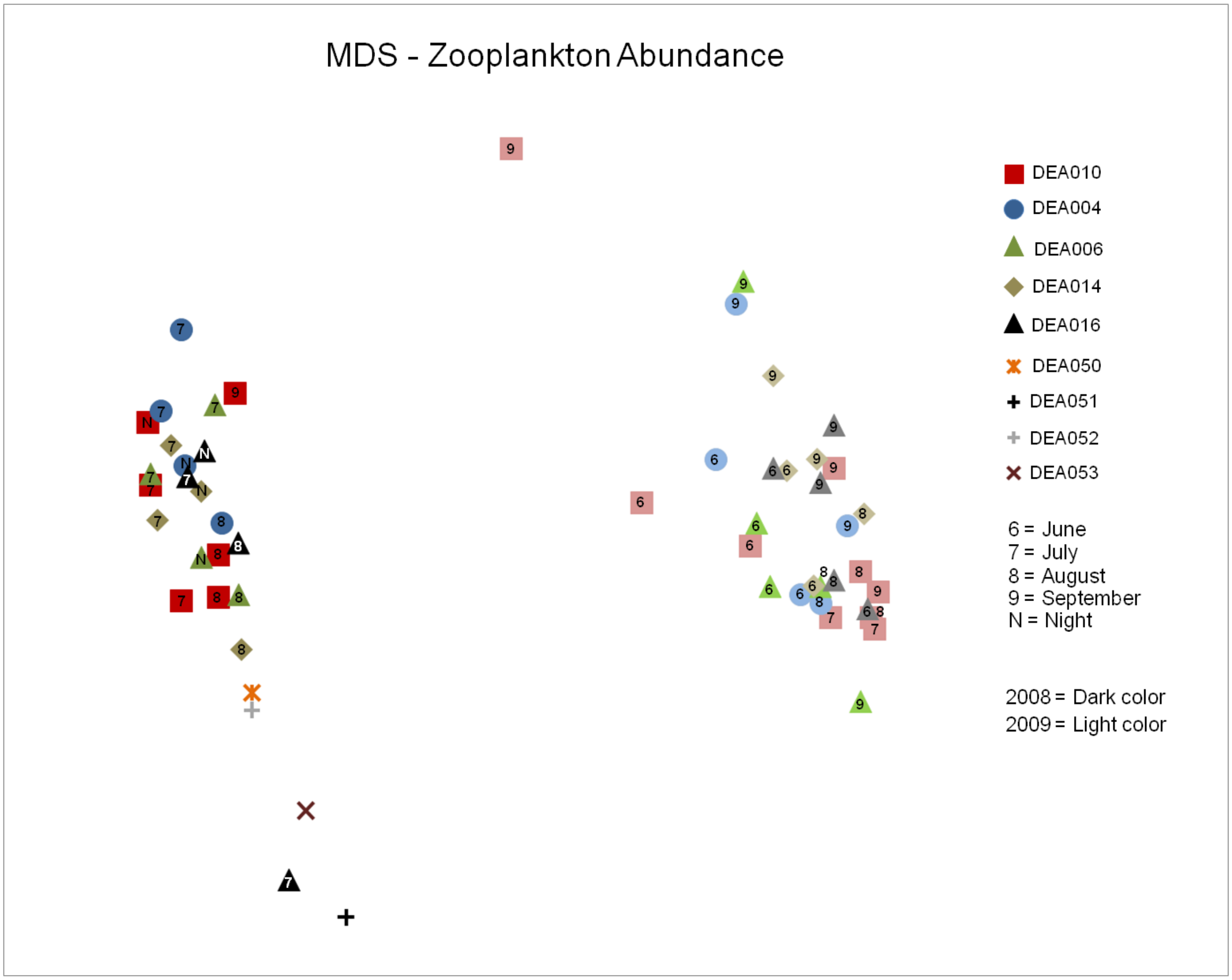

Figure 4. MDS plots of Deadwood Reservoir zooplankton abundance by site (Kruskal's stress value = 0.09). Points close together represent sites with similar community composition. Each site is assigned a shape and color. Years are distinguished by shades of the same color (dark =2008, light = 2009). Numbers contained within the points represent a sample month (6 = June, 7 = July, 8 = August, 9 = September, N = Night sampling from July 31, 2008).

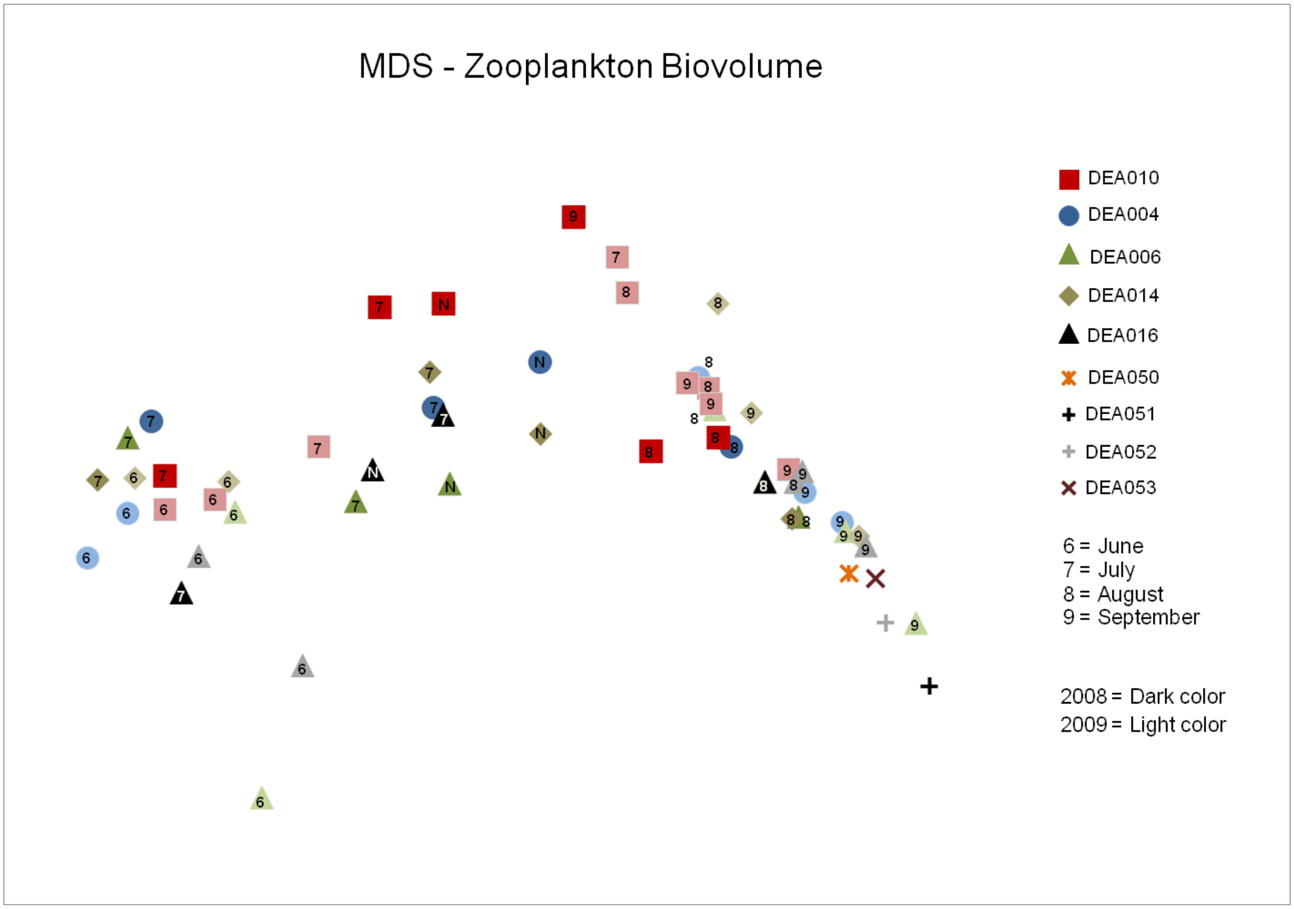

Figure 5. MDS plots of Deadwood Reservoir zooplankton biovolume by site (Kruskal's stress value = 0.07). Points close together represent sites with similar community composition. Each site is assigned a shape and color. Years are distinguished by shades of the same color (dark = 2008, light = 2009). Numbers contained within the points represent a sample month (6 = June, 7 = July, 8 = August, 9 = September, N = Night sampling from July 31, 2008).

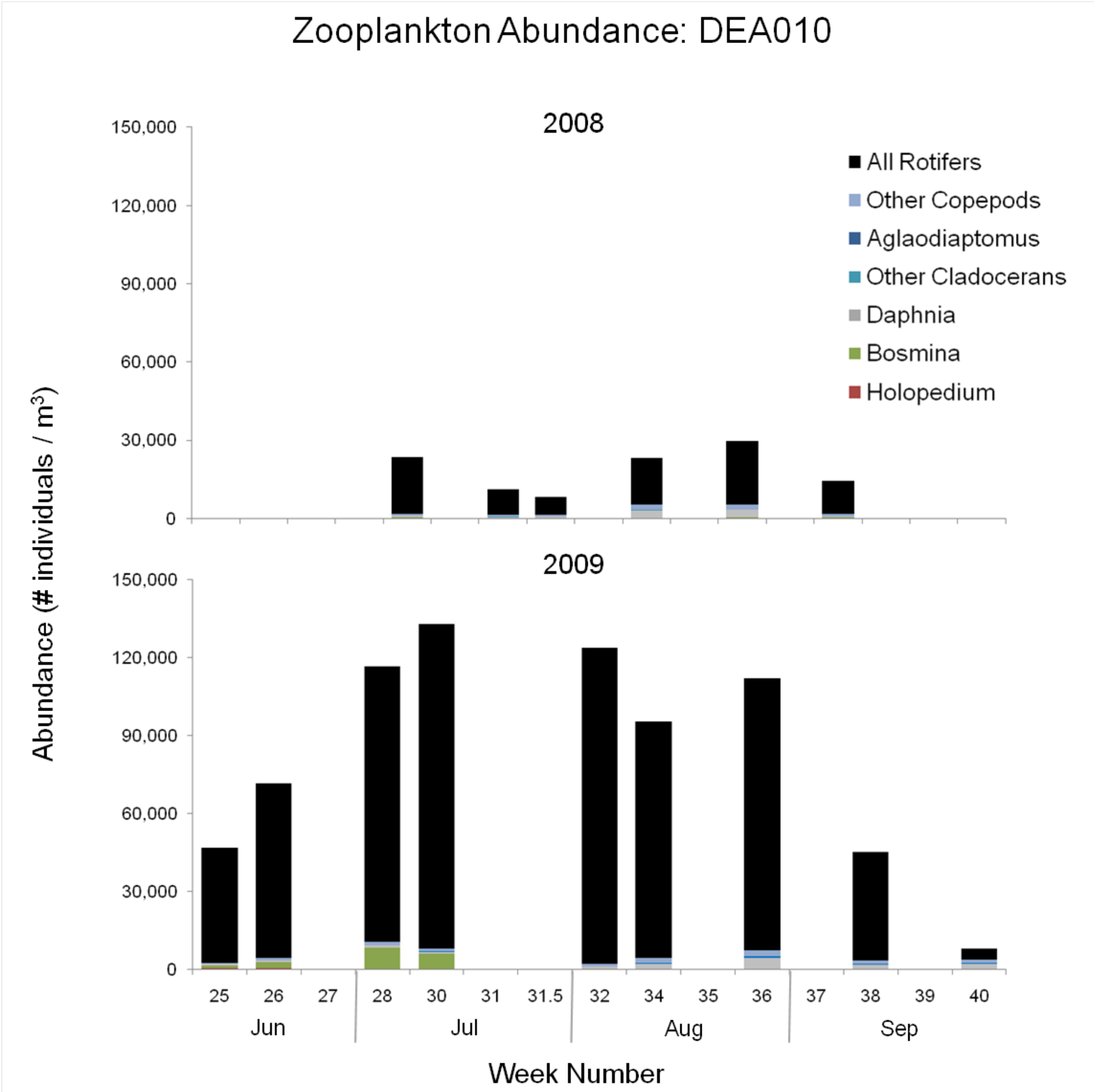

Figure 6. Abundance (# individuals / m^3) of dominant zooplankton taxa contributing to community composition at Site DEA010 over time.

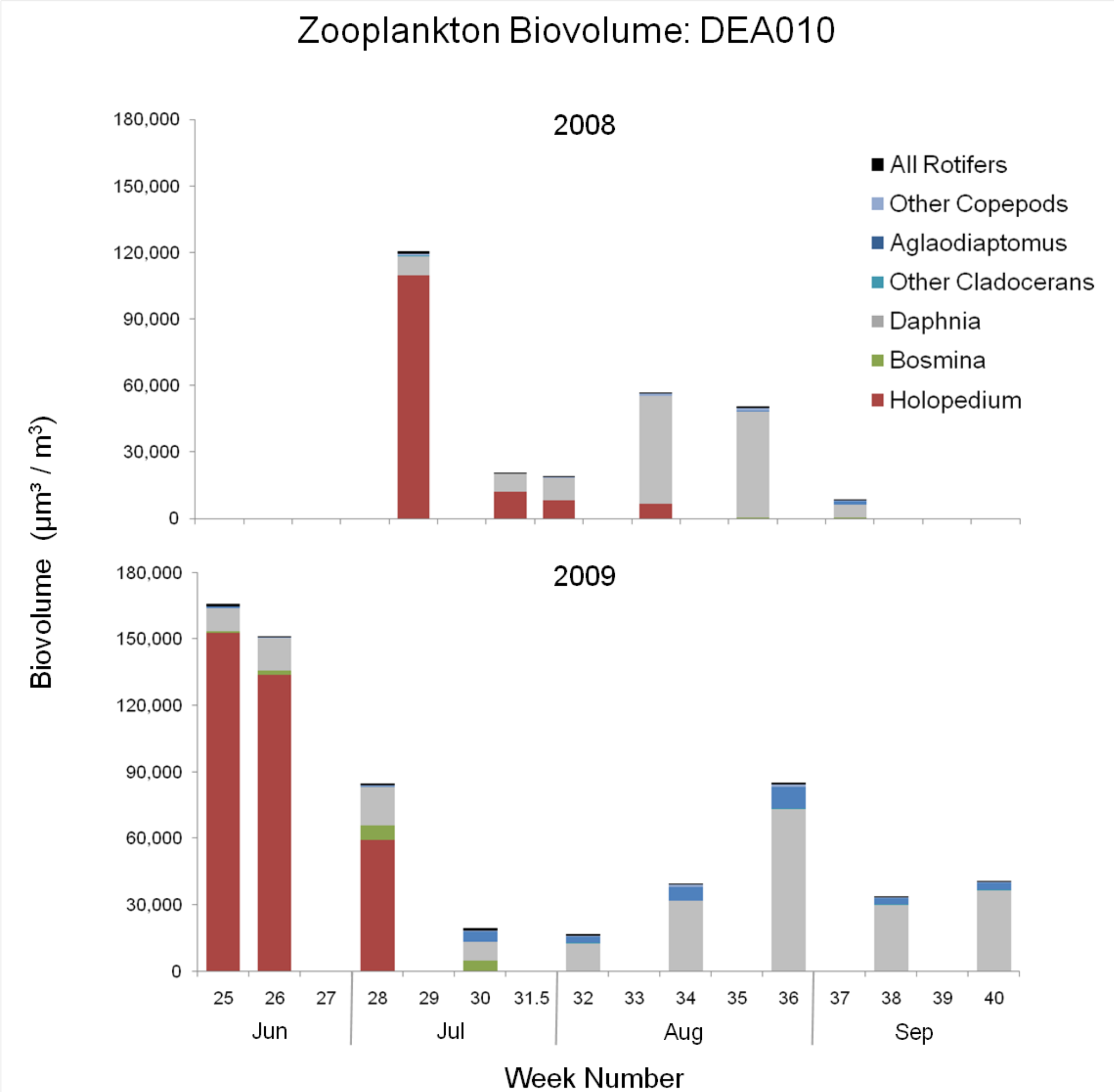

Figure 7. Biovolume of dominant zooplankton taxa contributing to community composition at Site DEA010 over time.

Phytoplankton Community Analysis

Phytoplankton biovolume data were available on six occasions in 2008 and nine occasions in 2009 at stations DEA004, DEA006, DEA010, DEA014 and DEA016 (N=58; Tables 2 and 4-5). Considering all samples, the community was dominated by the filamentous *cyanobacteria Anabaena spiroides*, constituting 48 percent of the biovolume across all measurements (Table 4). This was followed by the large, motile dinoflagellate *Ceratium hirundinella* (23 percent), and several diatom species of the genus *Fragilaria* (11 percent). Summing across phyla, those contributing more than 5 percent of the biovolume were cyanobacteria (51 percent), dinoflagellates (24 percent), diatoms (15 percent) and cryptophytes (8 percent). It should be noted, however, that the main dinoflagellate species *Ceratium hirundinella* was present in only 10 percent of samples (Table 4), thus the biovolume associated with this species was highly skewed to only a few, highly abundant, measurements.

Table 4. Dominant phytoplankton species and genera in the Deadwood Reservoir data set. The biovolume percentage refers to the contribution summed across all sampling dates and all stations. The occurrence indicates the percentage of samples in which that particular species appears.

Name	Group	Percent Biovolume	Percent Occurrence
Anabaena spiroides	Cyanobacteria	47.92%	100%
Ceratium hirundinella	Dinoflagellate	23.18%	10%
Fragilaria sp.	Diatom	10.51%	74%
Cryptomonas sp.	Cryptophyte	3.92%	93%
Ochromonas sp.	Cryptophyte	3.53%	17%
Aphanothece clathrata	Cyanobacteria	2.67%	48%
Synedra sp.	Diatom	2.20%	41%
Asterionella sp.	Diatom	2.03%	66%
Sphaerocystis sp.	Chlorophyte	1.27%	5%
Gymnodinium sp. (small)	Dinoflagellate	0.83%	33%
Rhodomonas lacustris var. nannoplanctica	Cryptophyte	0.36%	90%
Synura sp.	Chrysophyte	0.25%	2%
Phormidium sp.	Cyanobacteria	0.23%	43%
Rhodomonas sp.	Cryptophyte	0.20%	24%

Table 5. Dominant phytoplankton phyla in the Deadwood Reservoir data set. The biovolume percentage refers to the contribution summed across all sampling dates and all stations.

Group	Percent Biovolume
Cyanobacteria	50.82%
Dinoflagellate	24.01%
Diatom	14.75%
Cryptophyte	8.08%
Chlorophyte	1.45%
Chrysophyte	0.34%
Total	99.45%

Anabaena is a genus of cyanobacteria (also known as blue-green algae). They are filamentous, are able to fix atmospheric nitrogen via a heterocyst, and are known to form neurotoxins and taste and odor compounds such as geosmin and 2-methylisoborneol. They are typically found in eutrophic lakes, both stratified and shallow, with low nitrogen content as their nitrogen-fixing capability gives them a competitive advantage in these environments (Padisak, Crosetti, and Naselli-Flores 2009). They contain gas vesicles which aid buoyancy control and limit sedimentation losses in stratified environments (Walsby 1994). This species remained prevalent throughout the sampling period in both years.

Ceratium hirundinella is a large, motile, dinoflagellate species. Although slow-growing, the ability to perform large diurnal vertical migration to access nutrients and light gives it a competitive advantage in stratified environments. It is thus typically known as a species that appears in late summer in eutrophic, stratified lakes (Alexander and Imberger 2009), confirmed by its appearance in the Deadwood data set on only one occasion in the late summer in each year (10 Sept 2008 and 19 Aug 2009).

Diatoms were generally present in the early part of the stratification during the spring period. The diatom assemblage consisted of *Fragilaria*, *Asterionella* and *Synedra* species, with the Synedra species approximately 10 times larger based on biovolume. As with *Anabaena* and *Ceratium, Fragilaria* is also typically found in eutrophic systems (Padisak, Crosetti, and Naselli-Flores 2009).

Numerous cryptophyte species were prevalent, including species of *Cryptomonas*, *Ochromonas* and *Rhodomonas*, and were relatively persistent through the sampling period. Later in the stratification period, increasing concentrations of the large dinoflagellate *Ceratium hirundinella* and the small spherical cyanobacteria *Aphanothece clathrata* were observed. These species are known to prevail after extended periods of vertical stratification in nutrient-rich environments, and so their appearance towards the end of summer is expected.

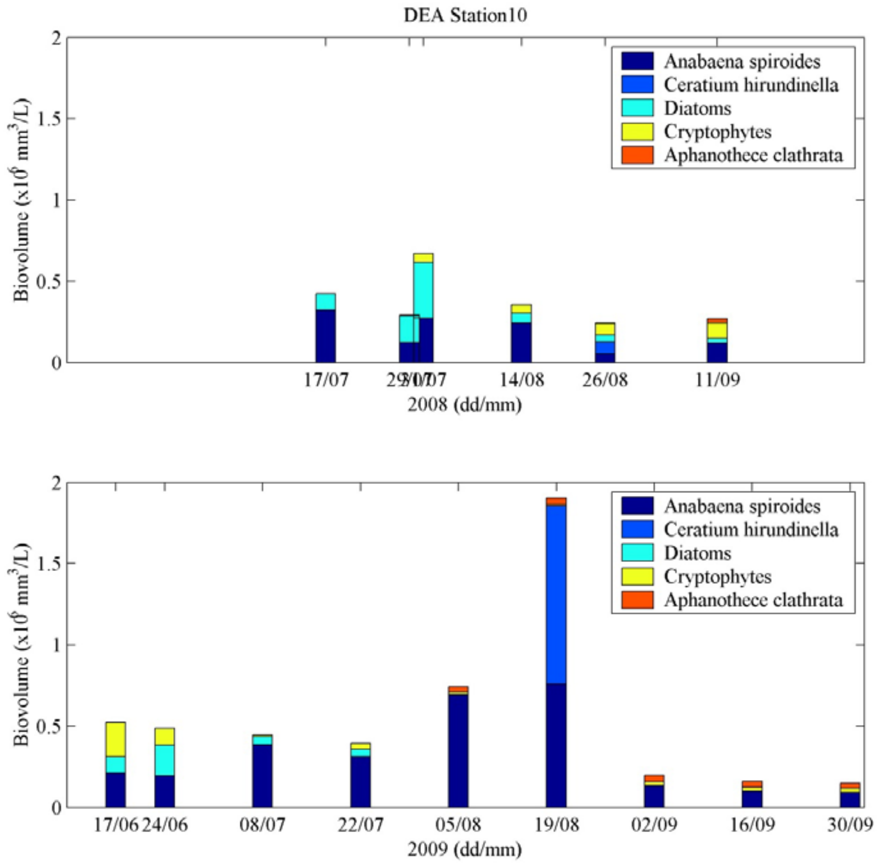

Figure 8. Biovolume of dominant species/groups in Deadwood Reservoir at station DEA010.

Phytoplankton Parameter Configuration in CAEDYM

On the basis of this information, approximately five groups can be used to describe the seasonal evolution of the phytoplankton community, as presented in Figure 8. The inclusion of *Ceratium hirundinella* was not considered, as although it makes up a significant component of the total biovolume, it only appears on one date in each year and the likelihood of simulating such an occurrence is low. Given that *Aphanothece clathrata* was also a small component of the overall biovolume, it was also excluded from the model.

A group configured to represent *Anabaena spiroides* was included, as this species is present in all samples and is the dominant component (48 percent) of the biovolume. A generic diatom group was included to account for the 15 percent of measured biovolume attributed to the genera *Fragilaria, Synedra,* and *Asterionella*. A group representing cryptophytes could also be included given they are present in more than 90 percent of samples and represent approximately 8 percent of the measured biovolume, but is not included in these simulations.

Previous simulations of the Deadwood Reservoir, configured prior to the receipt of the phytoplankton enumeration data, had two groups configured – one representative of a diatom group, and one representative of a eutrophic chlorophyte group. After the analysis of the phytoplankton data, model setup consisted of two groups configured to represent a eutrophic cyanobacteria group (*Anabaena spiroide*s) and a diatom group. One particular feature of the Deadwood Reservoir data set is the extremely low nitrogen (nitrate) concentrations, which have typically been below detection despite a reduction in the measurement limit from 0.01 mg L-1 in 2007 to 0.003 mg L-1 in 2008. The cyanobacteria group ultimately included in the model is configured to fix atmospheric nitrogen, as the prevalence of the species *Anabaena spiroides* and the below-detection dissolved inorganic nitrogen concentrations indicates this is an important feature of the ecosystem.

This requirement for the model would apparently be at odds with the eutrophic classification of the ecosystem based on species presence presented above; however, the through-ice sampling conducted in early 2008 is highly instructive in this regard. This measurement showed both the dissolved inorganic phosphorus and nitrogen concentrations to be higher than at any other time of the year, and the low dissolved oxygen measured at depth under the ice indicates the system is productive as substantial reserves of organic material are available in the sediment to draw down the oxygen substantially.

Model Performance

To quantitatively assess model performance due to changes in phytoplankton groups, correlation coefficient (r2), index of agreement (Willmott 1982), mean average error (MAE), and root mean square error (RMSE) were reported. Measurements (N=888 from 2007 – 2008) from the profiler for temperature, dissolved oxygen and chlorophyll-a at station DEA010 were used. Values for temperature, dissolved oxygen and chlorophyll-a were extracted from the model at the same depths and times to make a direct quantitative comparison.

Model skill results are presented in Table 6. Generally temperature is better represented by the model than dissolved oxygen, which in turn is better represented than chlorophyll-a. This is typically the case with all similar models, as the complexity increases when moving from physical (temperature) to chemical (dissolved oxygen) and biological (chlorophyll-a) variables. Inclusion of the new CAEDYM configuration ("New CAEDYM config") compared to the original ("Original") configuration saw marginal improvements in all chlorophyll-a metrics. MAE and RMSE were reduced by approximately 5 percent, and model skill increased by 7 percent. Although r2 is reported, it is generally accepted to be a poor indicator of model performance as the magnitude of r2 is not consistently related to the degree to which model-predicted observations approach the magnitudes of their observed counterparts (Willmott 1982).

After the incorporation of the new CAEDYM configuration, the complete model set-up was revisited to determine whether other opportunities for improvement existed. The phytoplankton data presented above removed a large proportion of the uncertainty about the phytoplankton community, however model improvements were only marginal as the original ‘guess’ as to what the community consisted of was relatively accurate.

Table 6. Model skill assessment for Deadwood Reservoir ELCOM-CAEDYM model over the period 2007-2008.

		Temperature	Dissolved oxygen	Chlorophyll-a
Original	r^2	0.93	0.20	0.02
	Skill index	0.96	0.65	0.43
	MAE	1.50	1.20	1.8
	RMSE	1.90	1.50	2.3
New CAEDYM config	r^2	0.94	0.18	0.03
	Skill index	0.97	0.64	0.46
	MAE	1.50	1.20	1.7
	RMSE	1.90	1.60	2.2
New CAEDYM + corrected discharge	r^2	0.97	0.40	0.07
	Skill index	0.99	0.76	0.54
	MAE	0.79	0.99	1.5
	RMSE	1.00	1.30	2.2

One important aspect of the simulations identified was that the temperature drawdown simulated during the summer releases was a potential candidate for improvement. Assessment of all the variables that affect this (meteorological conditions, internal mixing, inflows and outflows) identified that the simulation was strongly dependent on the outflow quantities. It had been previously assumed that measured values below the dam contained no measurement error, and thus any error in this measurement was propagated into the ungauged inflows via the water balance.

As this offtake is deep in the water column, and mixing at depth during summer is extremely weak, there is the potential to use the measured rate of drawdown of particular isotherms (lines of constant temperature) over time as a cross-check of the measured deep discharge flow rate. This was done over the period July 15 – August 2 2007, when the mean deep discharge rate was 22.54 m^3-1 (796.1 cfs). No spilling was occurring during this time and the gauged flows from the Deadwood River and Trail Creek were less than 2 m^3 s-1 combined. Using the LDS data, the change in storage volume of water less than a certain temperature was computed and compared to the measured discharge rate. Using a range of temperatures (7 - 10°C, at 0.5°C increments), the discharge flow rate determined over this period was 20.4 m^3 s-1, 90 percent of the measured value. This indicates a measurement error in the flows below the dam of approximately 10 to 11 percent, which seems entirely realistic.

We thus applied this correction to the measured deep discharge values, using 90 percent of the measured value, and compensating the ungauged inflows to account for this change. The results of the model simulations are presented in Figure 9 and Table 6 ("New CAEDYM + corrected discharge"). The improvement over the original simulations is excellent. Model skill for temperature is now 0.99 (up from 0.96), and both the mean average error and root mean square error are less than or equal to 1°C. Dissolved oxygen model skill improved from 0.65 to 0.76 (a 17 percent improvement), MAE decreased from 1.2 mg L-1 to 0.99 mg L-1 (17 percent improvement), and RMSE decreased from 1.5 mg L-1 to 1.3 mg L-1 (13 percent improvement). Model skill for chlorophyll-a increased by 26 percent to 0.54, MAE decreased by 17 percent to 1.5 micrograms of chlorophyll-a (μg chla) L-1, and RMSE decreased by 4 percent to 2.2 μg chla L-1.

With respect to the simulation of chlorophyll-a, the improvement in RMSE was entirely due to the change in the CAEDYM configuration, a decrease from 2.3 to 2.2 μg chla L-1 on the original simulations. The improvements in MAE were one-third due to the new CAEDYM configuration (a decrease from 1.8 to 1.7 μg chl-a L-1), and two-thirds due to the corrected water balance (a decrease from 1.7 to 1.5 μg chla L-1). The improvement in model skill was similarly due the new CAEDYM configuration (~30 percent) and approximately 70 percent due to the corrected water balance.

It should also be noted that the measurement of chlorophyll using the profiler is actually a measure of fluorescence and that extractive measurements of chlorophyll taken by bottle sample and analyzed in the laboratory are a more accurate measure. However, these measurements are far less numerous (N=36 points as opposed to N=888), and are only available in the surface layer at one point rather than as a profile.

Assessment of the model error for both measurements is presented in Table 7. These results indicate the importance of taking a holistic approach to the assessment of model skill. For example, the r^2 values for the extractive chlorophyll-a are far higher than for the profiler, however the skill index is lower. The MAE and RMSE are similar for both measurements, though perhaps slightly higher for the extractive chlorophyll-a.

Table 7. Model error assessment for different measurements of chlorophyll-a.

		Chlorophyll-a (profiler fluorescence)	**Chlorophyll-a (extractive)**
Original	r^2	0.02	0.04
	Skill index	0.43	0.17
	MAE	1.8	1.5
	RMSE	2.3	2.2
New CAEDYM config	r^2	0.03	0.16
	Skill index	0.46	0.03
	MAE	1.7	1.8
	RMSE	2.2	2.4
New CAEDYM + corrected discharge	r^2	0.07	0.3
	Skill index	0.54	0.04
	MAE	1.5	2.0
	RMSE	2.2	2.5

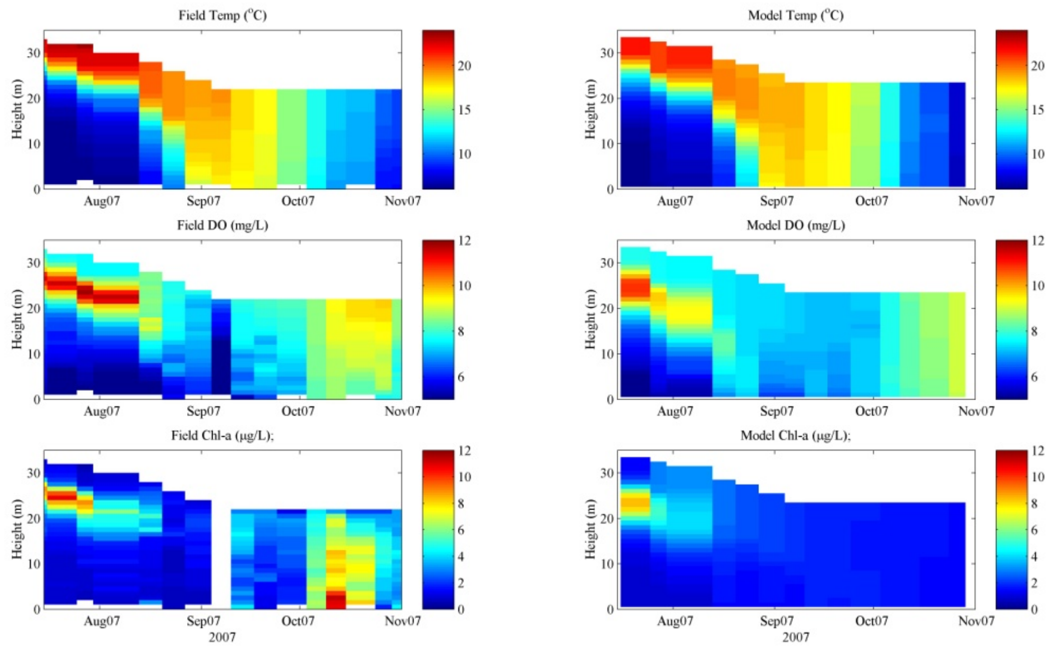

Figure 9. Comparison of measurements from Deadwood Reservoir in 2007 (left column) with simulated values (right column) for the new CAEDYM configuration and the corrected water balance. Model performance metrics are reported in Table 5.

SUMMARY AND CONCLUSIONS

In the broader Deadwood Reservoir ecosystem studies (Reclamation 2015), ELCOM-CAEDYM was used to simulate phytoplankton production for multiple scenarios of reservoir operations for dry, average, and wet water years. Field data for calibration and validation of ELCOM-CAEDYM were collected in the reservoir and tributary monitoring program from 2007 – 2011. We used the results of Science and Technology Program-funded plankton studies to inform model configuration.

Previous simulations of the Deadwood Reservoir, configured prior to the receipt of the phytoplankton count data, had two groups configured –a diatom group and a eutrophic chlorophyte group. Modifying phytoplankton parameters after considering plankton count data did not improve model performance much. Ultimately, two groups were configured to represent a eutrophic cyanobacteria group (*Anabaena spiroides*) and a diatom group.

In the case of Deadwood Reservoir, plankton sampling provided new data on zooplankton and phytoplankton community composition, but inclusion of new model parameters based off the community analysis did not improve ELCOM-CAEDYM model performance significantly. In other temperate systems, a preliminary plankton study of smaller scope (e.g., one site, monthly, for one season) could be used to describe major characteristics of plankton communities to guide model setup. Unusual results in the initial study might then suggest that a larger scale study of plankton dynamics is warranted. Barring unexpected findings, configuration of ELCOM-CAEDYM as is typical for temperate lakes will likely provide adequate model performance.

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